# HYDROGRAPHIC STUDY OF BARNEGAT BAY, NEW JERSEY

## Year 1 FINAL REPORT

Volume I

September 22, 1995
Division of Science and Research
New Jersey Department of Environmental Protection
Contract No. 48-106-000-105

Institute of Marine and Coastal Sciences
Contribution Number 95-19

# ERRATA

| | |
|---|---|
| Page 10 | Third line, after the word "where", insert "c stands for the concentration of a particular pollutant under study (e.g., nitrate); t stands for the time; x, y, and z stands for the distance in three directions;" |
| Page 23 | Thirteenth line, replace "©" with "(C)". |
| Page 24 | Fifteenth line, replace "©" with "(C)". |
| Page 92 | Twelfth line, add "+ $u_b$" to the equation. |
| Page 92 | Thirteenth line, add "+ $v_b$" to the equation. |

# Hydrographic Study of Barnegat Bay - Year 1 -

Volume I

Final Report Submitted by:

Dr. Qizhong Guo
Dr. Norbert P. Psuty
Mr. George P. Lordi
Dr. Scott Glenn
Mr. Matthew R. Mund

Rutgers - The State University of New Jersey
New Brunswick, New Jersey

to:
Division of Science and Research
New Jersey Department of Environmental Protection

In Connection with:
Contract No. 48-106-000-015
State of New Jersey

## Table of Contents

### Volume I


List of Figures iii

List of Tables vii

1.0 Preamble 1

2.0 Executive Summary 2

3.0 Statement of Problem 6

4.0 Cursory Review of Existing Numerical Circulation Models 11

4.1. Introduction 11
4.2. Zero-Dimension Single Mixed-Cell Models 16
4.3. Zero-Dimension Mixed-Cell In Series Models 27
4.4. One-Dimensional Models 29
4.5. Two-Dimensional Depth-Averaged Models 33
4.6. Three-Dimensional Models 38
4.7. Summary 42

5.0 Design of Field Collection Plan 43

5.1. Initial Selection of a Circulation Model for Field Data Collection Design 43
5.2. Field Data Requirements for Driving a Numerical Circulation Model 43
5.3. Field Data Requirements for Calibrating and Verifying a Numerical Circulation Models 44
5.4. Conceptual Data Collection Plan 44

6.0 Instruments and Their Deployment 46

6.1. S-4 Instrument 48
6.2. Marsh-McBirney Current Meters 53
6.3. CTD Instrument 57
6.4. Tidal gages 57
6.5. ADCP 62

7.0 Spatial and Temporal Field Data Assemblages 65

7.1. Instrument Locations 65

7.2. December/January Data Set 69
7.3. May/June Data Set 70
7.4. June/July Data Set 72
7.5. Comments on Applications of Field Data for Numerical Modeling 74

8.0 Preliminary Analysis of Circulation Pattern 75

8.1. Tidal Exchange Rate 75
8.2. Tidal Flushing Time 76
8.3. Horizontal Distribution of Salinity and Temperature 78
8.4. Vertical Distribution of Salinity and Temperature 87
8.5. Time Series Analysis of S-4 Current Velocity Data 87
8.6. Analysis of Marsh-McBirney Current Velocity Data 100
8.7. Analysis of ADCP Current Velocity Data 100
8.8. Summary of Circulation Pattern of Barnegat Bay 119

9.0 Preliminary Recommendation on Numerical Circulation Models 120

9.1. Recommendation for Two-Dimensional Depth-Averaged Models 121
9.2. Consideration of Layered Version of Three-Dimensional Models 122

10.0 Recommendations for Future Work 123

10.1. Additional Field Data Collection 123
10.2. Numerical Modeling 127

11.0 Summary and Conclusions 129

12.0 Implications for Management 132

13.0 Bibliography 134

14.0 Listing of All Participants and Activities on Project 138

**Volume II**

Appendix A: Specifications of Instruments
Appendix B: December/January Raw Data Set
Appendix C: May/June Raw Data Set
Appendix D: June/July Raw Data Set
Appendix E: Results of Time Series Analysis of S-4 Current Data

## List of Figures


Figure 3-1. Map of Barnegat Bay, New Jersey.

Figure 4-1. Schematic diagram of the input of hydrodynamic data to a lacustrine water quality model (Riley and Stefan, 1987)

Figure 4-2. Schematic diagram of the single well-mixed cell model.

Figure 4-3. Simulated nitrogen cycle (Cerco and Cole, 1993)

Figure 4-4. Diagenetic sediment model (Cerco and Cole, 1993)

Figure 4-5. Schematic illustration of the processes affecting the predicted chlorophyll-a concentration in each level of the biological submodel (Riley and Stefan, 1987)

Figure 4-6. Schematic of the two-cell model.

Figure 4-7. Representation of the link-node model network for WASP5 (Ambrose, 1991).

Figure 4-8. The finite element mesh for RMA2 (a component of two-dimensional model TABS-2) representing Galveston Bay. The mesh consisted of 3300 elements and 8200 nodes (Fast TAB manual).

Figure 4-9. Three-dimensional model CE-QUAL-ICM planform grid of Chesapeake Bay and gage locations (Johnson et al., 1993).

Figure 6-1. Method used to moor the S-4 instrument.

Figure 6-2. An example of current speed and direction output recorded by an S-4 instrument at Barnegat Inlet.

Figure 6-3. An example of temperature and salinity variation recorded by an S-4 instrument at Barnegat Inlet.

Figure 6-4. Marsh-McBirney current meter bi-directional transducer probe.

Figure 6-5. Method used to deploy Marsh-McBirney current meter.

Figure 6-6. Current velocity vertical profiles in North/South and East/West components recorded by the Marsh-McBirney current meter at Cedar Creek.

| | |
|---|---|
| Figure 6-7. | CTD instrument:<br>Left- CTD in cage, water intake located at bottom of cylinder.<br>Right- CTD records data as it is lowered through water column. |
| Figure 6-8. | An example of CTD temperature and salinity vertical profiles at Cedar Creek. |
| Figure 6-9. | Schematic of method used to deploy the SIGMA 950 Bubbler Transducer. |
| Figure 6-10. | An example of water surface elevation at Surf City recorded by the SIGMA 950 instrument. |
| Figure 6-11. | Acoustic Doppler Current Profiler:<br>Top- ADCP mounted on side of boat, recording along transect.<br>Bottom- Real time CRT display of vertical distribution of current velocity. |
| Figure 6-12. | An example of the velocity contour along a transect in Barnegat Bay recorded by the ADCP. |
| Figure 7-1. | Distribution of data collection points and transects in Barnegat Bay. |
| Figure 8-1. | Variation of tidal exchange rate with time at Barnegat Inlet, 6/22/95-7/11/95. |
| Figure 8-2. | Average salinity obtained by the S-4 in January, 1995. |
| Figure 8-3. | Average salinity obtained by the S-4 in May, 1995. |
| Figure 8-4. | Average salinity obtained by the S-4 in June/July, 1995. |
| Figure 8-5. | Average salinity obtained by CTD in May/June 1995. |
| Figure 8-6. | Average temperature obtained by S-4 in January 1995. |
| Figure 8-7. | Average temperature obtained by S-4 in May 1995. |
| Figure 8-8. | Average temperature obtained by S-4 in June/July 1995. |
| Figure 8-9. | Average temperature obtained by CTD in May/June 1995. |
| Figure 8-10. | Vertical distribution of temperature and salinity at Cedar Creek during flood tide. |
| Figure 8-11. | Vertical distribution of temperature and salinity at Cedar Creek during ebb tide. |

Figure 8-12. Vertical distribution of temperature and salinity at Silver Bay during flood tide.

Figure 8-13. Vertical distribution of temperature and salinity at Silver Bay during ebb tide.

Figure 8-14. Results of time series analysis of current data from S-4 instrument at Silver Bay, May 1995.

Figure 8-15. Results of time series analysis of current and wind data at Silver Bay, May 1995.

Figure 8-16. Cross-correlation between wind and current at Silver Bay, May 1995.

Figure 8-17. Results of time series analysis of current data from S-4 instrument at Loveladies, January 1995.

Figure 8-18. Results of time series analysis of current and wind data at Loveladies, January 1995.

Figure 8-19. Cross-correlation between wind and current at Loveladies, January 1995.

Figure 8-20. Map of Barnegat Bay showing locations of S-4 and Marsh-McBirney instruments.

Figure 8-21. Temporal variation of upper layer and lower layer current velocity at Cedar Creek, 5/30/95.

Figure 8-22. Vertical velocity distribution at Cedar Creek (North-South and East-West components), 1303, 5/30/95.

Figure 8-23. Vertical velocity distribution at Cedar Creek (North-South and East-West components, 1753, 5/30/95.

Figure 8-24. Temporal variation of wind speed (North-South and East-West components), 5/30/95.

Figure 8-25. Straw diagram showing current magnitude and direction from S-4 instrument at Cedar Creek, 5/30/95.

Figure 8-26. Temporal variations of upper layer and lower layer current velocity (North-South and East-West components) at Silver Bay, 6/1/95.

Figure 8-27. Vertical velocity distribution at Silver Bay (North-South and East-West components), 1433, 6/1/95.

Figure 8-28. Vertical velocity distribution at Silver Bay (North-South and East-West

components), 1634, 6/1/95.

Figure 8-29. Temporal variation of wind speed (North-South and East-West components), 6/1/95.

Figure 8-30. Straw diagram showing current magnitude and direction from S-4 instrument at Silver Bay, 6/1/95.

Figure 8-31. Silver Bay ADCP North-South velocity contour, 1408-1426, 6/8/95.

Figure 8-32. Silver Bay ADCP East-West velocity contour, 1408-1426, 6/8/95.

Figure 8-33. Silver Bay ADCP ship track and current velocity vector, 1408-1426, 6/8/95.

Figure 8-34. Silver Bay ADCP vertical velocity profile, 6/8/95.

Figure 8-35. Water surface elevation at Mantoloking visually read from stadia rod, 6/8/95.

Figure 8-36. Time variation of wind speed (North-South and East West components), Atlantic City, 6/8/95.

Figure 8-37. Straw diagram of current speed vectors from S-4 instrument at Mantoloking on 6/8/95.

## List of Tables


Table 4-1. Summary of Reviewed Circulation Models and their Output Variables

Table 4-2. Summary of Major Assumptions and Applicabilities of Models of Various Dimensions

Table 6-1. Instrumentation and Data Collected

## 1.0 Preamble

This report is presented to the Division of Science and Research of the New Jersey Department of Environmental Protection in fulfillment of Contract No. 48-106-000-015, Hydrographic Study of Barnegat Bay.

This report consists of data sets gathered in Barnegat that portray the spatial and temporal variations of the specific characteristics of the Bay, including current flows, salinities, temperatures, and water elevations. These are original data sets whose purpose is to lead to the development of a numerical circulation model of the Bay.

This report also reviews estuarine circulation models which may be appropriate to Barnegat Bay. It recommends a class of model that is used to direct the data gathering effort so as to accumulate measurements useful to the running of the model.

Within the constraints of a budget limitation and the time available to collect field data, this report submits a large data set collected within Barnegat Bay over periods from December 1994 through July 1995. This data and their analyses are presented to yield the following:

a. A set of field data which can be used to run, calibrate, and verify a numerical circulation model.

b. An assessment of the circulation pattern and its impacts on transport of pollutants based on the field data collected.

c. A recommendation of a numerical circulation model for detailed hydrographic study of Barnegat Bay.

## 2.0 Executive Summary

2.1 Introduction.

There is considerable concern regarding the water quality in Barnegat Bay. Excessive quantities of nutrients as well as pathogens are entering the Bay through various sources and are being distributed by the ambient circulation processes. Driven by the forces associated with lunar tides, winds, and freshwater flows into the bay, the circulation pattern of Barnegat Bay is a complex interaction of these forces with the subaqueous topography and coastal inlets. Although general knowledge of the bay's circulation is known, it is at a coarse scale and data are largely lacking in regard to measurements over extended periods and in different parts of the bay.

Thus one component of this report is to improve upon the data set that exists for Barnegat Bay by collecting hydrographic data pertaining to the flows and exchanges within the Bay and between the Bay and the Ocean. Another component is to analyze the collected data and assess the information relative to the development of a circulation pattern. However, in an effort to maximize the utility of the collected data, it was proposed that the data be appropriate as input to numerical simulation models that can be run to represent the conditions in Barnegat Bay. Therefore, a third component of this report is to review applicable circulation models and to determine which may be most appropriate for Barnegat Bay. There is a degree of feedback between the models and the data. The field measurements help to determine the complexity of the real world situations and they help to focus on models that can simulate that level of complexity, thereby optimizing the need for input data and the sophistication required of the model. Together, the review of existing models and the data collection will combine to present a final component of the report which is to recommend a numerical simulation model capable of representing the conditions which characterize Barnegat Bay.

Because we have gathered and analyzed new data from the Bay, it is likely that new information has meaning for the broad objectives related to the water quality in the Bay and management programs to be undertaken. In this regard, an ancillary product of our field investigation and model review is the significance of our findings and the extension of our determinations to the management decisions that may be exercised in the future.

2.2 Review of Numerical Circulation Models

Each category of the numerical circulation models can make some contribution to the understanding of the transfers and exchanges in Barnegat Bay. The simplest model (zero-dimension) provides average conditions for the Bay as an entire unit. Whereas this is not a correct representation of the variable components of the Bay, it is a useful approach to generate a general descriptive calculation. One-dimensional models increase the level of complexity and permit a simulation that can incorporate the downstream gradient and the differences between the characteristics near the Inlet versus the characteristics at the southern and northern portions of the Bay. However, to incorporate the cross-bay differences, those near the landward margin versus those near the seaward margin, it is necessary to advance to a two-dimensional model. At this level, the two-dimensional model assumes that the Bay is well-mixed in the vertical direction and the gradients are in the horizontal plane. Therefore, the depth-averaged two-dimensional model can accommodate the gradients established by the freshwater discharge as well as those caused by the marine exchanges at the Inlet. Only in those situations when the Bay is stratified vertically or with strong vertical current, will it be necessary to consider using a three-dimensional model to account for differences through depth.

A recommendation is made to use a depth-averaged, two-dimensional model at this time to represent the conditions in Barnegat Bay.

### 2.3 Data Collected in Barnegat Bay

Rather than just compile a suite of measurements, this report generates data sets appropriate to drive, calibrate, and verify the hydrodynamic components of a proposed water quality circulation model. Three temporal sets of data were collected on flow, salinity, temperature, and water elevation. One set was in December/January; another in May; and another in June/July. These time periods represent differing climate and weather conditions and therefore they portray different magnitudes of the forces driving circulation in the Bay. Most of the instruments gathered data continuously for one month. Some of the instruments operated for shorter continuous intervals, and some collected spot measurements during a tidal cycle.

The spatial deployment of the instruments was established to record data at the inflow locations, at the outflow locations, and within the Bay. In some instances, the instruments were situated at a single point at the margin of the Bay or within the Bay. In other situations, the instruments were moved along a transect of the Bay, through the vertical water column, or both. In this way, information was gathered to determine vertical and horizontal gradients, and whether the Bay was well-mixed or stratified.

Together, the data sets offer new insights into the spatial and temporal patterns of flow and exchanges within the bay under varying conditions.

### 2.4 Analysis and Application of Data

Among the information included in the data sets is a portrayal of the complex interaction among the water flow inputs and the topography of the bay. There is a horizontal salinity gradient from Barnegat Inlet toward both the north and south. Temperature is fairly uniform in the Bay during the summer, whereas there is a spatial gradient away from the Inlet in the winter. In general, the vertical salinity and temperature values show that the bay is well mixed. However, some instances of stratification were observed during the data collection program. Cross-bay circulation driven by wind can be seen in the data, producing two-layer flow; this is a complexity that makes the simple models (zero-dimensional and one-dimensional models) inappropriate for modeling the circulation pattern of Barnegat Bay.

Flushing time, the time it would take a pollutant to be moved through the bay by the action of the tidal exchange, is very long. Our calculations suggest that the average flood tide brings in a volume that is about thirty-seven percent new ocean water and about sixty-three percent returned Bay water. As a result of the large volume of water in Barnegat Bay and the very limited exchange during the tidal input, our calculation is that the flushing time is about 58 days, or 100 tidal cycles.

An unknown quantity of fresh groundwater may be entering the Bay through direct discharge along the margins rather than through the streams discharging into the Bay. This is a perplexing issue because of the problems of measurement and, subsequently, problems related to efforts to ameliorate its effects. In Barnegat Bay, it appears that the direct inputs from groundwater are minimal and may be excluded from consideration at this stage in the analysis.

Whereas the present effort has generated a considerable amount of new information on water flow characteristics and circulation, improvements to the data sets and to the understanding of circulation are needed. The recommended two-dimensional model may be the most appropriate to represent Barnegat Bay circulation, but there is a possibility that a three-dimensional model may be required. Additional information on flows and circulation will be addressed in a second-year data collection program. Additional variables on environmental characteristics will also be needed to complement the circulation model.

## 2.5 Implications for Management

The preliminary selection of a depth-averaged two-dimensional circulation model has considerable implication for management. Initially, it suggests that the data needs to run this model are less difficult to measure and collect than those of a three-dimensional model. Further, our data indicate that vertical stratification is a less common event and that there is restricted application of the more complex models.

Two important management considerations have resulted from the data gathering and analyses of the first year's program. One of these is that the direct groundwater source is very limited and may be dropped from the calculations in the running of the circulation model. This is an important statement because it means that the landward contributions to water quality in the Bay are mostly derived from the streams and the watersheds. That is, that although there is percolation and ground water movement, nearly all of the rainfall exits the watersheds through a combination of direct runoff and groundwater contributions to the streams before they discharge into Barnegat Bay. From a management perspective, it means that it is possible to sample watershed outputs and determine the efficacy of water quality programs enacted in the watersheds.

The other management consideration pertains to the ocean inputs through the Inlet. Our calculations indicate that the ocean is a source of inputs to the Bay and these inputs could be part of the pollutant load measured within parts of the Bay. It is known that the quality of the ocean water is related to the discharges into the inshore marine system. Discharges from water treatment facilities, from outfalls, and from any inshore sources which discharge into the ocean could enter Barnegat Bay through Barnegat Inlet and become part of the Bay's pollutant burden. Therefore, a Bay water quality management program must extend to the mixing zone on the ocean side of the Inlet and must consider sources of pollutants interring the mixing zone by coastal drift. The tidal exchange rate obtained through this project will help to define the magnitude of the mixing zone in the ocean, and will determine that portion of the shoreface wastewater discharges that will enter the Bay.

## 3.0 Statement of Problem

### 3.1. Current Water Quality Conditions of the Bay

Barnegat Bay in Ocean County, New Jersey (Fig. 3-1), provides essential habitat for many species of fish and shellfish and is one of the most widely used recreational and commercial fishing areas in NJ. And similar to estuaries elsewhere, Barnegat Bay is currently experiencing development pressure which is adversely affecting its water quality and ecology.

Water quality in the Bay is being degraded primarily by nonpoint sources of pollution. Current conditions in the Bay appear to reflect excessive nutrient inputs, resulting in high levels of phytoplankton growth and turbidity. Bacterial pollution is also evident in the Bay, as indicated by water quality monitoring and shellfish bed restrictions. Bacterial pollution has resulted in direct impairment of human use of the Bay by resulting in restrictions on swimming and shellfish harvesting.

It is expected that the primary cause of this nonpoint-source pollution is development on land and the activities associated with development (e.g., vehicle use, lawn and garden maintenance, septic systems), although other sources, such as boats and wildlife populations, are contributors to the pollution problem (NJDEPE, 1993).

The past decade has seen a massive effort to collect and treat all sewage produced by coastal development, with long outfalls discharging the effluent to nearshore ocean waters beyond the barrier islands. This control of sewage sources increases the relative importance of the nonpoint sources of pollution to the Bay.

### 3.2. Pathways of Nonpoint Source Pollutants to the Bay

Nutrients and pathogens can be carried to the Bay by surface stormwater runoff (through streams leading to the Bay or direct runoff) and/or by groundwater seepage.

Barnegat Bay is dominated by relatively small river basins (a total of 22 river sub-basins) and areas of direct drainage (RGH, 1990). The Manasquan River, which forms the northern edge of the study area, drains to Barnegat Bay through the Point Pleasant Canal. The total drainage area for the Bay is 286,659 acres. The Toms River, the largest river in the drainage basin, occupies 42% of the drainage area. Other significant rivers are: Cedar Creek (12%), Metedeconk River (11%), and Forked River (5.7%).

In general, the hydrologic cycle (the circulation of water through rainfall, stream flow, and evapotranspiration) in the New Jersey coastal plain is quite different from inland watersheds (Martin, 1989). Of the 45 in. of annual rainfall, only a small fraction enters surface streams as direct runoff (2.5 in./year), whereas 20 in./year infiltrates rapidly to the shallow groundwater table. The rest (22.5

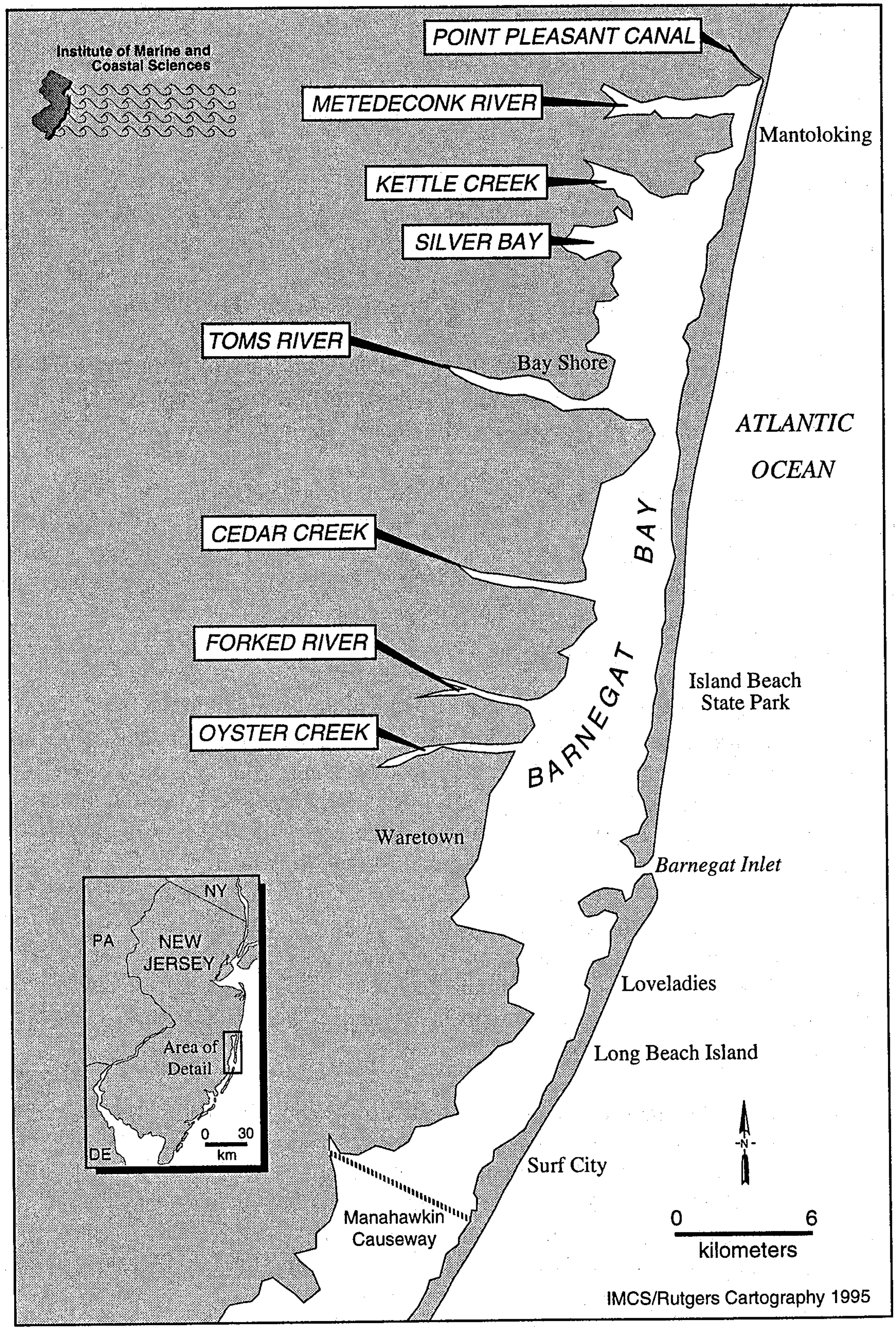



Figure 3-1. Map of Barnegat Bay, New Jersey

in./yr) is evapotranspiration, water uses, and leakage to the deep aquifer. The water uses include all types of water consumption. Among the portion infiltrated (20 in./year), most of it (17 in./year) discharges to surface streams as groundwater flow. The result is a longer, more attenuated surface stream hydrograph (i.e., longer duration and smaller peak stream flow) in coastal plain locations, with subsurface flow playing a far greater role than in upland watersheds. Watt et al. (1994) have recently conducted a specific hydrologic study of the confined aquifer system under the northern Barnegat Bay watershed, whose conclusions are in agreement with the general coastal plain condition of ameliorated flow rates.

### 3.3. Physical Conditions Affecting Pollutant Transport in the Bay

Transport of pollutants in the Bay is determined by the circulation pattern. Circulation refers to the mixing of Bay water that occurs as a result of currents. In Barnegat Bay, currents are generated by winds, tidal forces, and the flow of rivers into the bay.

With its long axis extending roughly north-south for approximately 30 miles and paralleling the mainland, Barnegat Bay forms an irregular tidal basin ranging from 1.25 to 4 miles in width. Due to the elongated shape and openness of the Bay and its relative shallowness, it is likely that winds are a significant source of Bay currents. The principal wind directions in Barnegat Bay are from the south, west, and northwest. In general, summer winds usually come from the south, and winter winds are usually from the northwest and west.

Tidal variation also affects currents and the depth of water within the Bay. Tidal inflow of salt water occurs through Barnegat and Manasquan Inlets (in the latter case, salt water enters the Bay via the Point Pleasant Canal). The water may also exchange with the Little Egg Harbor at the southern boundary. The mean tidal range at Barnegat Inlet is 3.1 feet. Within the Bay, the tidal range drops as the water is distributed to the west, north, and south. The mean tidal range at some representative areas of the bay are: Mantoloking, 0.34 feet; Waretown, 0.34 feet; Bayshore (Toms River), 0.37 ft; and Loveladies, 0.46 ft (1977-78 data). Tidal elevation changes have occurred as a result of the south jetty modification and associated dredging at Barnegat Inlet (Gebert, 1994). The gage record at the inlet shows a pre- to post-new south jetty tidal range increase of about 40%. Additionally, sites within the bay record similar increases in tidal range. Mean tidal ranges in 1993 are as follows: Mantoloking, 0.47 ft, Waretown, 0.44 ft; Bayshore, 0.52 ft; and Loveladies, 0.56 ft., and they also substantially increase.

In Barnegat Bay, most of the freshwater enters the estuary from surface streams and ground water seepage along the mainland. The mean surface flow from all of the tributaries totals about 360 $ft^3$/sec (Chizmadia et al., 1984). Toms River has by far the greatest freshwater flow (200 $ft^3$/sec), followed by Cedar Creek (110 $ft^3$/sec). The amount of direct runoff into the Bay is expected to be small and negligible. The portion of infiltrated water that bypasses surface streams and discharges directly into the Bay is relatively minor according to U.S.G.S.; direct ground water seepage input to the Bay is roughly 10 $ft^3$/sec (Nicholson, 1995).

Circulation within the Bay is also influenced by extreme conditions such as hurricane and northeast storm events.

Barnegat Bay is a shallow estuary, attaining a maximum depth of only about 13 feet and averaging 4.6 feet. In general, the eastern perimeter of the Bay is shallower than the central and western portions, and it is deepest along the Intracoastal Waterway (which is dredged to maintain a depth of 6 to 12 feet). Therefore, much of the flow in the interior portions of the Bay occurs along the dredged channels.

Because of its shallowness, the temperature, which also affects density, is expected to be quite uniform in the vertical direction, and will not play a significant role in the circulation pattern.

In summary, the pollutant transport in the Bay is affected by the forcing variables of winds, tidal currents, river and ground water inflows, which interact with the bathymetry of the Bay.

### 3.4. Need for Complete Understanding of Circulation Pattern

Prior to about 1950, the approach to pollution problems and circulation in bays was based on the tidal-prism exchange concept. In classical tidal prism theory it was assumed that the water brought into an estuary on the flood tide is completely mixed with the polluted estuarine waters over a one tidal cycle. Therefore, each tide dilutes and replaces some portion of the estuary volume. The flushing rate is a function of the volume of the tidal prism relative to the estuary volume.

The volume of water in Barnegat Bay was estimated to be 238,000,000 $m^3$ (1974 data). The tidal prism was measured to be 11,200,000 $m^3$ (1980 data). Based on the classical tidal prism theory, complete turnover of Barnegat Bay takes place every 21 tidal cycles, or approximately 11 days. Such an estimation of pollutant flushing time is not adequate for Barnegat Bay for the following three reasons:

(1) The basic assumption of the tidal-prism theory is invalid, due to incomplete mixing within the estuary.
(2) The pollutants are being introduced from several sources unevenly distributed within the Bay, therefore, the turnover time, even if estimated correctly, can not be applied to all pollutant sources.
(3) The circulation in the Bay is probably driven more by winds than tides.

Since 1950, pollution analysis has been developed within the framework of mass transport theory. In the mass transport theory, a water body is divided into compartments, and the total mass flow (advection) and diffusion into an individual compartment is made equal to the flow and diffusion out of the compartment. However, in the classical tidal prism theory, the entire bay is treated as a compartment, and only mass flow (advection) in and out of the compartment is considered, .i.e., diffusion is not considered. The mass transport theory can be described completely by the following three-dimensional equation:

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x}(D_x\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(D_y\frac{\partial c}{\partial y})+\frac{\partial}{\partial z}(D_z\frac{\partial c}{\partial z})+Source-Sink$$

where u, v, and w represent mean (ensemble average, not tidal average) current velocities in three directions; $D_x$, $D_y$, and $D_z$ represent diffusion coefficients in three directions resulting from turbulent fluctuation, molecular diffusion, salinity gradient, and temperature gradient. Normally, the current velocity (non-tidally averaged) is much more significant in affecting pollutant transport than the diffusion. If the current velocity and the diffusion coefficient are known, the transport of the pollutant is well defined by the above equation. Thus, the current velocity (i.e., circulation pattern) and the diffusion coefficient need to be determined for this Bay to fully describe the pollutant transport using the mass transport approach.

In theory, the current velocities in three directions can be measured directly by available instruments. However, as pointed out above, the current velocity pattern is affected by winds, tides, river, and ground water inflows. To measure the current velocity under various conditions at sufficient resolution for the entire Bay is a formidable task. Further, the diffusion coefficient is primarily related to turbulent fluctuation and density gradient, and it is almost impossible to measure these variations directly with sufficient resolution.

Therefore, the approach pursued in this project is to apply a numerical model by gathering flow velocity and salinity data in the field and by deriving diffusion characteristics from the model. All of the field data collections described in this report were designed to gather temporal and spatial data in support of the model development and verification.

### 3.5. Benefits and Relevance to DEP/State Needs

In response to a growing concern about the impacts of development, the New Jersey Legislature passed an Act requiring a study of the nature and extent of development impacts upon the Bay. To assess the impacts, a water quality model will need to be established. The pollutant transport process in the Bay is critical to the water quality, and the transport is mostly determined by the circulation pattern.

This study provides the necessary hydrographic information to drive, calibrate, and verify the hydrodynamic (transport) component of a proposed water quality model, something which is lacking at present. This research project's benefits and relevance to DEP/State needs will be further described in the last section entitled "Implications for Management."

## 4.0 Cursory Review of Existing Numerical Circulation Models

### 4..1. Introduction

The purpose of this review of existing estuarine circulation models is to aid the design of the field data collection plan, and the field data collection is the primary objective of the research project. This review also recommends an appropriate circulation model for Barnegat Bay; this is another objective of the research project. Model reviews presented here are "cursory" and by no means detailed. To apply any of the existing models, it is recommended that an in-depth study be made before-hand.

A circulation model is defined herein as a model which can simulate water flow velocity, tidal elevation, salinity, and water temperature. A schematic diagram of a lake water quality model is shown in Fig. 4-1 to demonstrate how the circulation (hydrodynamic) model fits into the overall water quality model.

Models reviewed are listed in Table 4-1. Besides the models which exist in published form, various agencies and individuals were contacted for model descriptions and manuals. Special attention was paid to those models which have been used for New Jersey bays and estuaries.

Existing circulation models vary in spatial dimensions and method of solutions. The major assumptions and applicabilities of circulation models of various dimensions are summarized in Table 4-2. The cursory review is presented in the order of spatial dimensions.

The approach of the review follows a sequence of steps that put the models and their attributes in perspective. These steps are:

- Define the category of model
- Identify and define the numerical solution
- Define the field measurements needed to run the model

A summary review of the various models is included at the end of the chapter. It incorporates discussion of the attributes/limitations to Barnegat Bay.

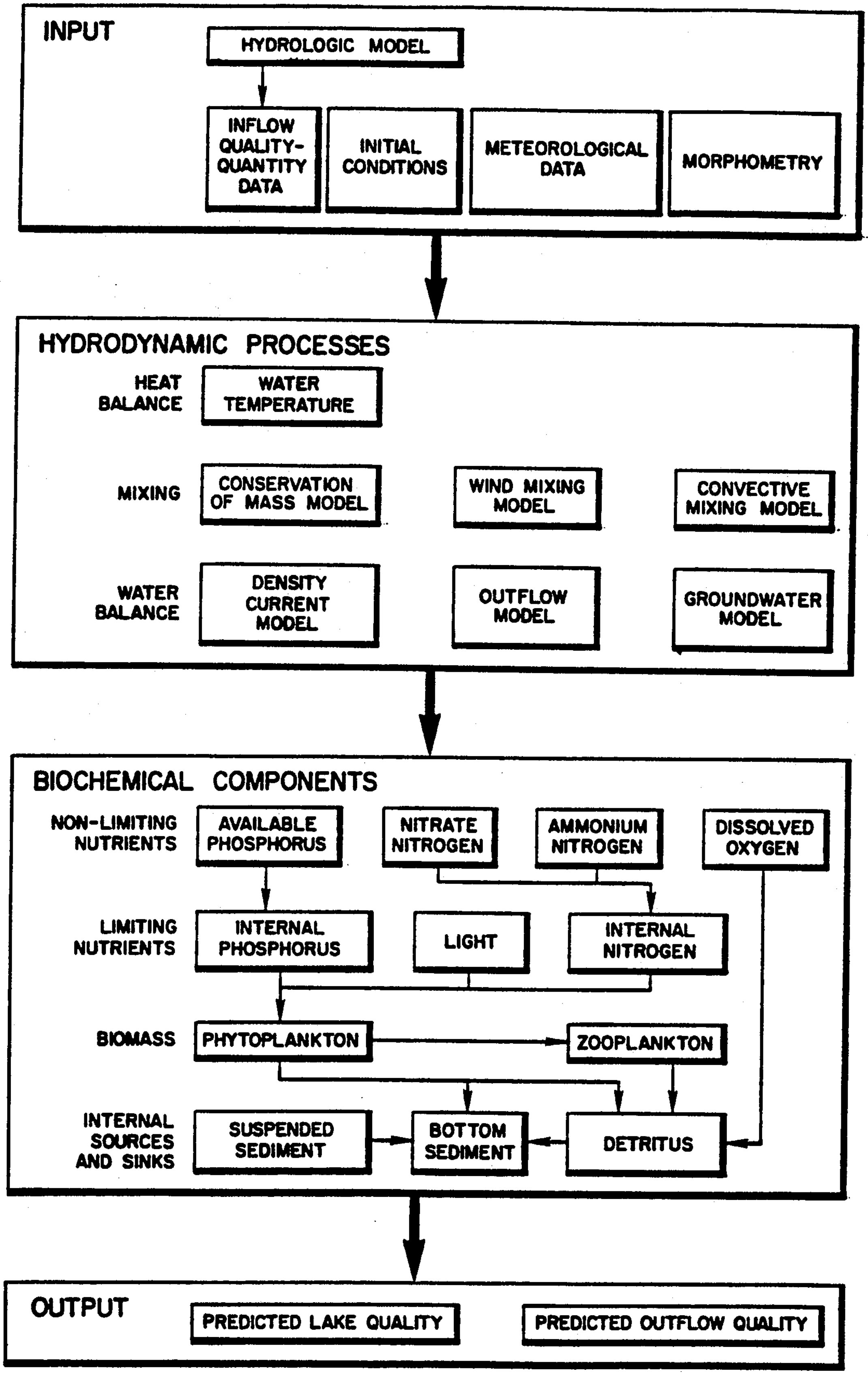



Figure 4-1. Schematic diagram of the input of hydrodynamic data to a lacustrine water quality model (Riley and Stefan, 1987)

## TABLE 4-1. SUMMARY OF REVIEWED CIRCULATION MODELS AND THEIR OUTPUT VARIABLES

| MODEL | DIMENSION | Method of Solution | OUTPUT VARIABLE | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Current Velocity | Tidal Elevation | Salinity | Temperature | D.O. | Chlorophyl-a |
| Single Mixed-Cell Model | 0D | AG* | YES | YES | YES | YES | YES | YES |
| Mixed-Cell In- Series Model | 0D | AG | YES | YES | YES | YES | YES | YES |
| DEM | 1D & quasi-2D | FD** | YES | YES | YES | NO | YES | YES |
| WASP5 | 1D & quasi-2D | FD | YES | YES | YES | NO | YES | YES |
| MIT-DNM | 1D | FE*** | YES | YES | YES | YES | YES | YES |
| TABS-2 | 2D | FE | YES | YES | YES | NO | NO | NO |
| DYNLET | 1D | FD | YES | YES | NO | NO | NO | NO |
| TRIM | 2D | FD | YES | YES | YES | NO | NO | NO |
| CLHYD | 2D | FD | YES | YES | NO | NO | NO | NO |
| WIFM | 2D | FD | YES | YES | NO | NO | NO | NO |
| HYDTID | 2D | FD | YES | YES | YES | NO | NO | NO |
| TABS-MD | 1D, 2D & 3D | FE | YES | YES | YES | NO | NO | NO |
| CH3D-WES & CE-QUAL-ICM | 2D & 3D | FD | YES | YES | YES | YES | YES | YES |
| ECOM-si | 3D | FD | YES | YES | YES | YES | NO | NO |

* AG - Algebraic Method

** Finite Difference Method

*** Finite Element Method

**TABLE 4-2. Summary of Major Assumptions and Applicabilities of Models of Various Dimensions**

| Dimension | Example Models | Major Assumptions | Applicability to Barnegat Bay |
|---|---|---|---|
| Zero-Dimension | Classical tidal prism model, Modified tidal prism model, Tidal exchange model, Model based on mass balance on one, two, or more cells. | 1. Only storage of substance is considered, and flow direction is not a factor.<br><br>2. Everything is assumed to be fully mixed, i.e., concentration is assumed to be constant in each cell. | Not recommended for final model.<br><br>Classical tidal prism model and one-cell mass balance model, when made equivalent to tidal exchange model, will give averaged condition for the entire Bay. Recommended for obtaining average Bay condition, but not recommended for final model.<br><br>When correct number of cells is used, modified tidal prism model and multi-cell mass balance model will give spatial condition in the Bay. However, it is difficult to determine correct number of cells for Barnegat Bay. |
| One-Dimension | DEM,<br><br>WASP5,<br><br>MIT-DNM<br><br>DYNLET | 1. Primary current direction is pre-imposed instead of solved by model.<br><br>2. Variation of concentration is only allowed in the longitudinal direction. | Not recommended for final model.<br><br>Reasons: Primary current direction is unknown, especially under windy condition, and concentration varies both in longitudinal (N-S) and transverse (E-W) directions in Barnegat Bay. |

**TABLE 4-2 (Continued). Summary of Major Assumptions and Applicabilities of Models of Various Dimensions**

| Dimension | Example Models | Major Assumptions | Applicability to Barnegat Bay |
|---|---|---|---|
| Two-Dimension (Depth-Averaged) | TAB-2, TRIM, CLHYD, WIFM, HYDTID, CH3D-WES (2-D mode) | 1. Primary flow is along the horizontal plane (two directions).<br><br>2. The Bay is fully mixed in the vertical direction, i.e., concentration is uniform in the vertical direction. Concentration variation is allowed and solved for the horizontal plane (N-S and E-W directions). | Preliminarily recommended for Barnegat Bay.<br><br>Concentration is generally uniform in the vertical direction. However, primary flow may not always along the horizontal plane, especially under windy condition. Further field data collection is needed to verify the first model assumption. (Sufficient field data have been collected through this project to drive, calibrate, and verify a two-dimensional depth-averaged model.) |
| Three-Dimension | TABS-MD, CH3D-WES, ECOM-si | 1. Flows in all directions are allowed and solved by the model.<br><br>2. Concentration variations in all directions are allowed and solved by the model. | Not recommended for Barnegat Bay at this stage, until further field data collection proves the necessity for a three-dimensional model.<br><br>Because of the shallowness of the Bay, a simplified version of the three-dimensional model can be used. Three-dimensional models require much more field data than two dimensional depth-averaged models (at least double for a two-layer version). Existing field data are insufficient to drive, calibrate, and verify a three-dimensional model. |

### 4.2. Zero Dimension Single Well-Mixed Cell Models

A schematic diagram for the single well-mixed cell model is shown in Fig. 4-2. In the single well-mixed cell, the entire bay is treated as one cell, and salinity, temperature. and concentration are assumed to be uniform within the entire bay. Water and substances are allowed to enter and leave the cell. In unsteady models, the mass balance approach means that the difference between input and output is equal to storage. In steady state models, the concept of mass balance approach assumes that input equals output.

#### 4.2.1. The Tidally-Averaged Model

This model considers total inflow and outflow of water as well as other variables (such as salinity, nitrate, sediment) over a tidal cycle, for the entire bay.

- Mass Balance for Water:

$$Q_R T + V_F - V_E + Q_G T + PAT - EAT = 0$$

where

$Q_R$ = the river flow rate into the bay,
T = the tidal period,
$V_F$ = the tidal flow volume during the flood tide,
$V_E$ = the tidal flow volume during ebb tide,
$Q_G$ = the ground water flow rate into the bay,
P = the precipitation intensity,
A = the surface area of the bay,
E = the evaporation intensity.

- Mass Balance for Salinity:

$$V_F S_F = V_E S$$

where

$S_F$ = the averaged salinity during flood tide,
S = the averaged salinity within the Bay (if the bay is fully mixed, the averaged salinity within the bay should be equal to the averaged salinity at the ocean inlet during ebb tide).

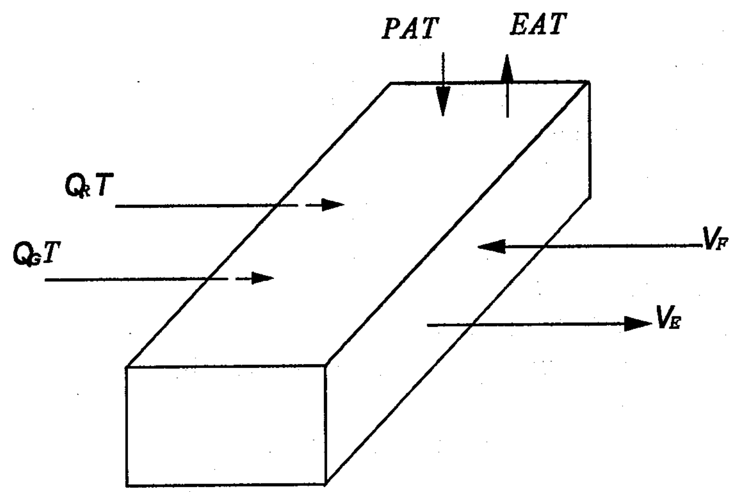



*Figure 4-2. Schematic diagram of single well-mixed cell model*

• Mass Balance for Nitrate:

$$Q_R T C_R + V_F C_F - V_E C + Q_G T C_G + PATC_P + \text{Nitrification} + \text{Sediment Release} - \text{Uptake}$$

where

$Q_R$ = the river flow rate into the bay,
T = the tidal period,
$C_R$ = the concentration of the nitrate in the river inflow,
$V_F$ = the flood tide volume,
A = the surface area of the bay,
$C_F$ = the concentration of nitrate in the tidal water,
$V_E$ = the tidal flow volume during ebb tide,
C = the concentration of nitrate in the bay,
$Q_G$ = the ground water flow rate into the bay,
$C_G$ = the concentration of nitrate in the groundwater inflow,
P = the precipitation intensity,
$C_P$ = the concentration of nitrate in the precipitation.

The nitrogen cycle (nitrification process as a component) and sediment diagenesis (sediment nutrient release as an outcome) simulated by Cerco and Cole (1993) are shown in Figs. 4-3 and 4-4 respectively. The uptake of nutrients simulated by Riley and Stefan (1987) is shown in Fig. 4-5. Note that the nitrate is used as an example of a dissolved substance in the model description.

• Field Data Needs:

Hydrographic data:

$Q_R$ = the river flow rate into the bay,
$V_F$ = the flood tide volume,
P = the precipitation intensity,
A = the surface area of the bay
E = the evaporation intensity,
$S_F$ = the averaged salinity during flood tide,
S = the averaged salinity within the bay.

Chemical-biochemical data:

$C_R$ = the concentration of the nitrate in the river inflow,
$C_T$ = the concentration of nitrate in the tidal water,
$C_G$ = the concentration of substance in the groundwater inflow,
$C_P$ = the concentration of nitrate in the precipitation,

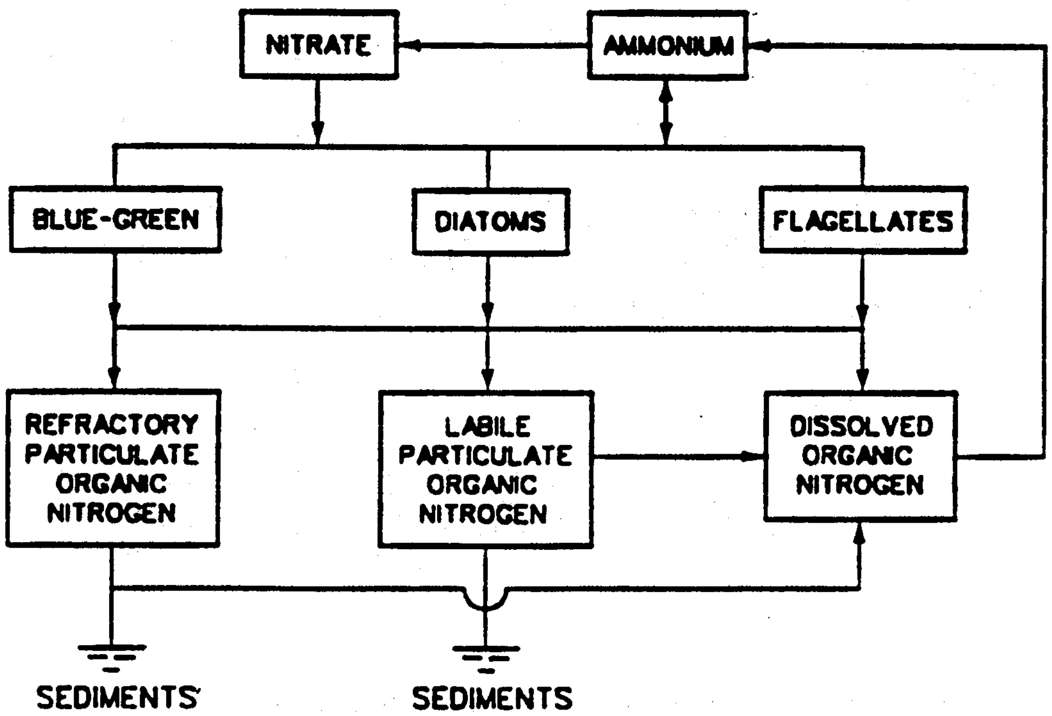



Figure 4-3. Simulated nitrogen cycle (Cerco and Cole, 1993)

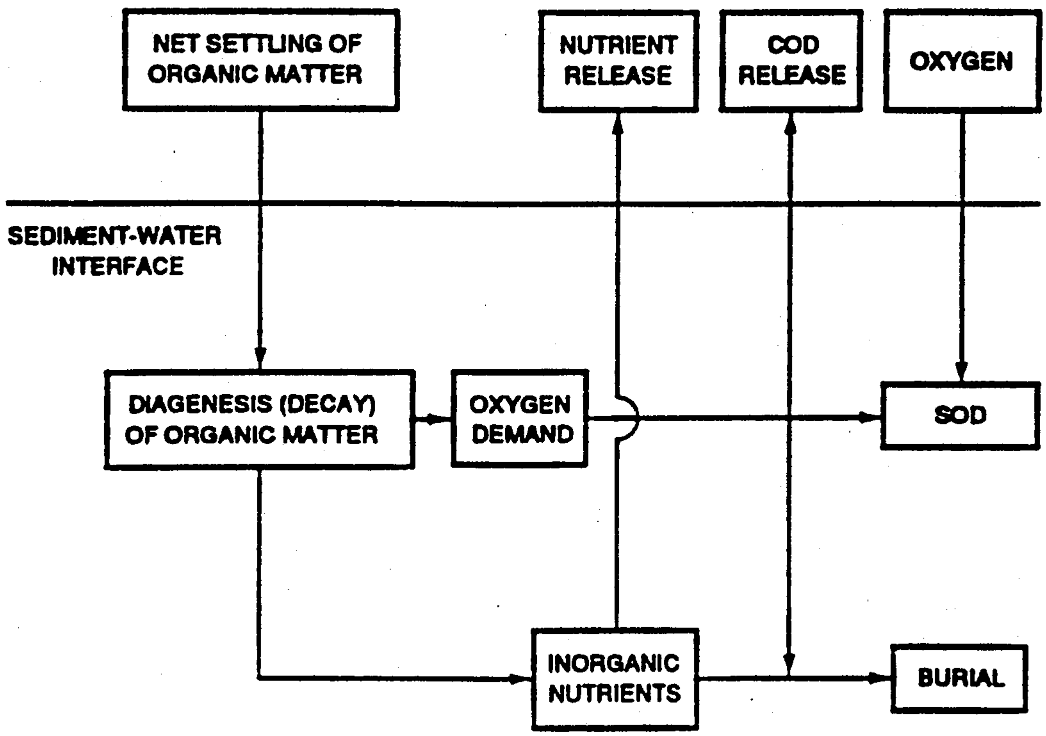
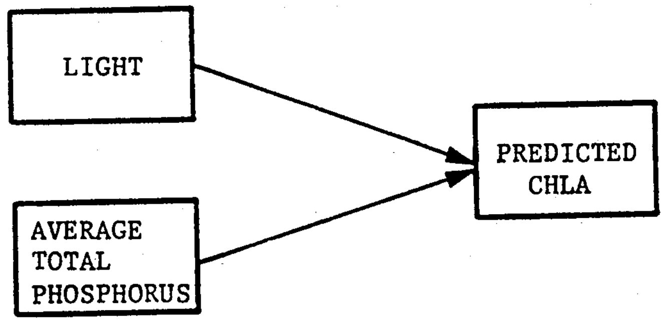
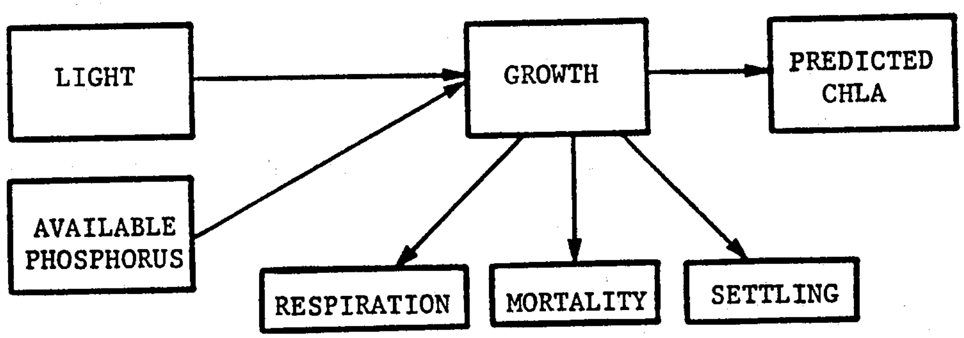



Figure 4-4. Diagenetic sediment model (Cerco and Cole, 1993)

Level 1: Analysis for the entire mixed layer




Level 2: Analysis for individual layers




Level 3: Analysis for individual layers

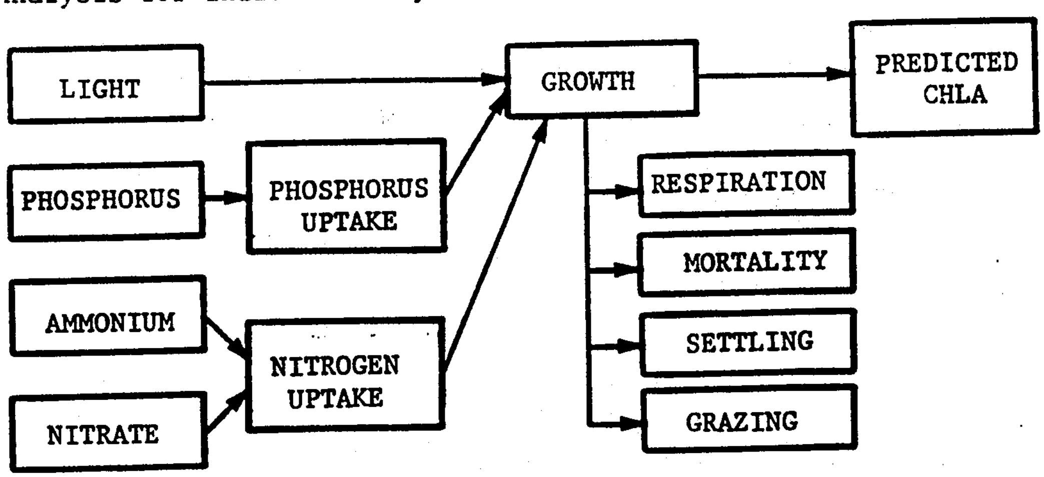



Figure 4-5. Schematic illustration of the processes affecting the predicted chlorophyll-a concentration in each level of the biological submodel (Riley and Stefan, 1987)

Rates of nitrification, sediment release, and uptake.

- Solution:

a. The mass balance equation for salinity is used to solve for the ebb tidal volume ($V_E$),

$$V_E = \frac{V_F S_F}{S}$$

b. The mass balance equation for water is used to solve for the groundwater inflow rate ($Q_G$),

$$Q_G = \frac{-Q_{RT} - V_F + V_E - PAT + EAT}{T}$$

c. The mass balance equation for nitrate is used to solve for nitrate concentration (C),

$$C = \frac{Q_R T C_R + V_F C_F + Q_G T C_G + PATC_P}{Q_R T + Q_G T + PAT - EAT + V_F}$$

if the processes of nitrification, sediment release, and uptake are ignored.

4.2.2. Classical Tidal Prism Model

The classical tidal prism model assumes that the water brought into a bay on the flood tide is completely mixed with the polluted bay water over a tidal cycle

- The tidal prism ($V_P$) is defined as

$$V_P = V_F + Q_R T + Q_G T + PAT - EAT$$

where

$V_P$ = the tidal prism,
$V_F$ = the tidal inflow volume during the flood tide,
$Q_R$ = the river flow rate into the bay,
T = the tidal period,
$Q_G$ = the ground water flow rate into the bay,

P = the precipitation intensity,
A = the surface area of the bay,
E = the evaporation intensity.

- The flushing time ($T_F$) is defined as (Ippen, 1966)

$$T_F = \frac{V}{V_P} T$$

where

$T_F$ = the flushing time,
V = the volume of water in the bay,
$V_P$ = the tidal prism,
T = the tidal period.

- Salinity (S) in the bay can be calculated as (based on dilution)

$$S = [1 - \frac{(Q_R + Q_G + PA - EA)\, T_F}{V}]\, S_F$$

- Concentration of nitrate © can be calculated as (based on dilution)

$$C = \frac{Q_R T C_R}{Q_R T + Q_G T + PAT - EAT + V_F}$$

This is the same value as that obtained from the tidally-averaged mass balance equation in section 4.2.1., if the river inflow is assumed to be the only source of nitrate.

- Field data needs

The same as those for the tidally-averaged mass balance equation in Section 4.2.1.

4.2.3. Tidal Exchange Model

- Tidal exchange rate (R) is defined as (Fisher et al., 1979)

$$R=\frac{V_0}{V_F}$$

where

$V_0$ = the volume of new ocean water entering the bay on the flood tide,
$V_F$ = the total volume of water entering the bay on the flood tide.

- Tidal exchange rate

With known salinity, the tidal exchange rate can be calculated as

$$R=\frac{S_F-S_E}{S_0-S_E}$$

where

$S_F$ = the average salinity of water entering the bay on the flood tide,
$S_E$ = the average salinity of water leaving the bay on the ebb tide,
$S_0$ = the salinity of ocean water.

- Concentration of nitrate in the bay

The total flow available for diluting the pollutant associated with fresh river flow is

$$Q_D=\frac{2V_0}{T}+Q_R+Q_G+PA-EA$$

The mean concentration of nitrate © can be calculated as

$$C=\frac{Q_R T C_R}{Q_R T+Q_G T+PAT-EAT+V_0}$$

This is a different calculation method than that produced by the mass balance model and by the classical tidal prism model. Instead of the total volume of water entering the bay on the flood tide ($V_F$), the volume of new ocean water entering the bay on the flood tide ($V_0$) is used for dilution in the tidal exchange model. In this case, the rate of delivery of new ocean water is less than the tidal inflow and the rate of dilution is slowed.

4.2.4. Unsteady Model

Unsteady models are variations of the models described above except that they incorporate some change in storage in the bay within the tidal cycle.

- Mass Balance for Water:

$$\frac{dV}{dt}=\sum Q_R+\sum Q_F+\sum Q_E+\sum Q_G+PA-EA$$

where

V = the volume of water in the bay as a function of the tidal elevation ($\eta$),
t = the time,
$Q_R$ = the river flow rate into the bay,
$Q_F$ = the flow rate into the bay during the flood tide,
$Q_E$ = the flow rate out of the bay during the ebb tide,
$Q_G$ = the ground water flow rate into the bay,
P = the precipitation intensity,
A = the surface area of the bay,
E = the evaporation intensity.

- Mass Balance for Salinity:

$$\frac{d(VS)}{dt}=\sum Q_F S_F+\sum Q_E S$$

where

V = the volume of water in the bay as a function of the tidal elevation ($\eta$),
S = the salinity of water in the bay,
t = the time,
$Q_F$ = the flow rate into the bay during the flood tide,
$S_F$ = the salinity of tidal water into the bay during the flood tide,
$Q_E$ = the flow rate out of the bay during the ebb tide.

- Mass Balance for Nitrate:

$$\frac{dVC}{dt}=Q_R C_R+Q_F C_F+Q_E C+Q_G C_G+PAC_G+Nitrification+SedimentRelease-Uptake$$

where

V = the volume of water in the bay as a function of the tidal elevation ($\eta$),

$C$ = the concentration of nitrate in the bay,
$t$ = the time,
$Q_R$ = the river flow rate into the bay,
$C_R$ = the concentration of nitrate in river inflow,
$Q_F$ = the flow rate into the bay during the flood tide,
$C_F$ = the concentration of nitrate in the flood-tidal water,
$Q_E$ = the flow rate out of the bay during the ebb tide,
$Q_G$ = the ground water flow rate into the bay,
$C_G$ = the concentration of nitrate in the groundwater inflow,
$P$ = the precipitation intensity,
$A$ = the surface area of the bay,
$C_P$ = the concentration of nitrate in the precipitation.

- Field Data Needs:

Hydrographic data needs:

$V_0$ = Initial volume of water in the bay,
$\eta_0$ = Initial tidal elevation in the bay,
$\eta$ = Variation of tidal elevation with time,
$V$ = Volume of water in the bay as a function of the tidal elevation ($\eta$),
$Q_R$ = the river flow rate into the bay,
$Q_F$ = the flow rate into the bay during the flood tide,
$S_F$ = the salinity of tidal water into the bay during the flood tide,
$S$ = the salinity in the bay,
$P$ = the precipitation intensity,
$A$ = the area of the bay,
$E$ = the evaporation intensity,

Chemical-Biochemical data needs:

$C_0$ = initial concentration in the bay,
$C_R$ = the concentration of the nitrate in the river inflow,
$C_F$ = the concentration of nitrate in the tidal water,
$C_G$ = the concentration of nitrate in the groundwater inflow,
$C_P$ = the concentration of nitrate in the precipitation,
Rates of nitrification, sediment release, and uptake.

- Solution for Substance Concentration:

a. The mass balance equation for salinity is used to solve for the ebb tidal volume ($V_E$).
b. The mass balance equation for water is used to solve for the groundwater inflow rate ($Q_G$).

c. The mass balance equation for nitrate is used to solve for nitrate concentration (C).

Note: A computer program needs to be written to solve the above equations.

## 4.3. Zero-Dimension Mixed Cells In-Series Models

### 4.3.1. Two-Cell Model

The two-cell model is sketched in Fig. 4-6. It assumes that water is fully mixed in each individual cells. For each individual cell, the mass balance equation is the same as that for the single-cell model.

### 4.3.2. Multiple-Cell Model

The bay is divided into multiple cells in the multiple-cell model. The number of cells could be chosen to mimic the one-dimensional advection-diffusion mass transport model. If an infinite number of cells is used, it is equivalent to the plug-flow situation (i.e., purely advection).

### 4.3.3. The Modified Tidal Prism Model

The basic assumption of the classical tidal prism theory is invalid, due to incomplete mixing within the estuary over a tidal cycle. In the modified tidal prism model (Ippen, 1966), the bay is divided in segments. Within each segment it is assumed that there is complete mixing at high tide. It was proposed that the length of a segment be defined by the average length of the tidal excursion, since this is the largest segment in which complete mixing by the tide can be assumed. The tidal excursion is defined as the average distance traveled by a particle of water on the flood tide. The segment so defined would contain, at high tide, a volume equal to that contained in the adjacent seaward segment at low tide. The innermost segment is defined as the section above which the volume required to raise the level of the water from low to high tide is equal to the volume contributed by the river during one tidal cycle.

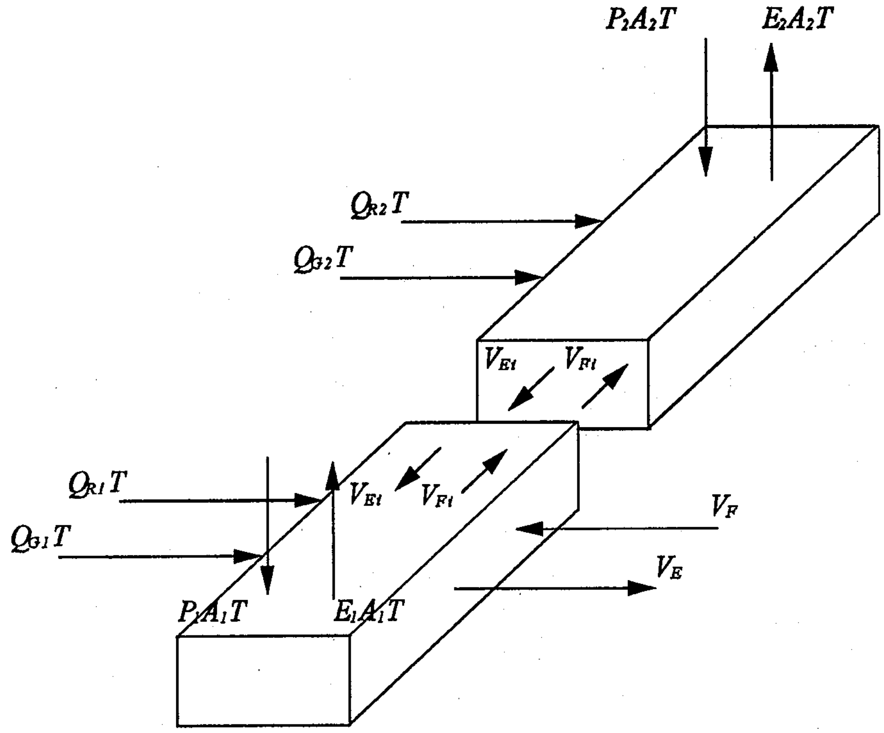



*Figure 4-6. Schematic of the two-cell model*

### 4.4. One-Dimensional Models

There are many variations of one-, two-, and three- dimensional models. These models are described for model-specific cases.

#### 4.4.1. WASP5 (Water Analysis System Program) and DEM (Dynamic Estuary Model)

- Introduction

WASP5 and the Dynamic Estuary Model are not appropriate for simulating the circulation pattern in Barnegat Bay.

The most comprehensive one-dimensional estuarine water quality model is WASP5 (Ambrose, et al., 1991), which is an extension of the Dynamic Estuary Model (Feigner and Harris, 1970). The WASP5 modeling system consists of two stand-alone computer programs, DYNHYD5 and WASP5, that can be run in conjunction or separately. The hydrodynamics program, DYNHYD5, simulates the movement and interaction of pollutants within the water. The latter program is supplied with two kinetic sub-models (EUTRO4 and TOXI4) to simulate two of the major classes of water quality problems: conventional pollution (dissolved oxygen, biochemical oxygen demand, nutrients, and eutrophication) and toxic pollution (organic chemicals, heavy metals, and sediments).

The hydrodynamics component of the WASP5 modeling system, DYNHYD5, solves the one-dimensional equations of continuity and momentum for a branching or channel-junction (link-node) computational network. At each time step, the equation of motion is solved at the links (channels), giving velocities for mass transport calculations, and the equation of continuity is solved at the nodes (junctions), giving heads (storage) for pollutant concentration calculations. The model network is shown in Fig. 4-7.

Link-node networks can treat fairly complex branching flow patterns and irregular shorelines with acceptable accuracy for many studies. However, they can not handle stratified water bodies, small streams, or rivers with a steep bottom slope. Link-node networks can be set up for wide, shallow water bodies if primary flow directions are well defined. For this latter reason, this one-dimensional model is also called a quasi-two dimensional model.

The Dynamic Estuary Model and the TOXI component of WASP have been applied to the Delaware Estuary. A model similar to an earlier version of DYNHYD5 was applied by Najjar (1989) to simulate tidal elevation and current velocity in Lakes Bay, New Jersey. It seems that tidal elevation was simulated well in comparison to what was measured in the field. Current velocity was not measured during the field data collection, thus the simulated current velocity was not verified. More field data are needed to confirm applicability of this quasi-two dimensional model to Lakes Bay.

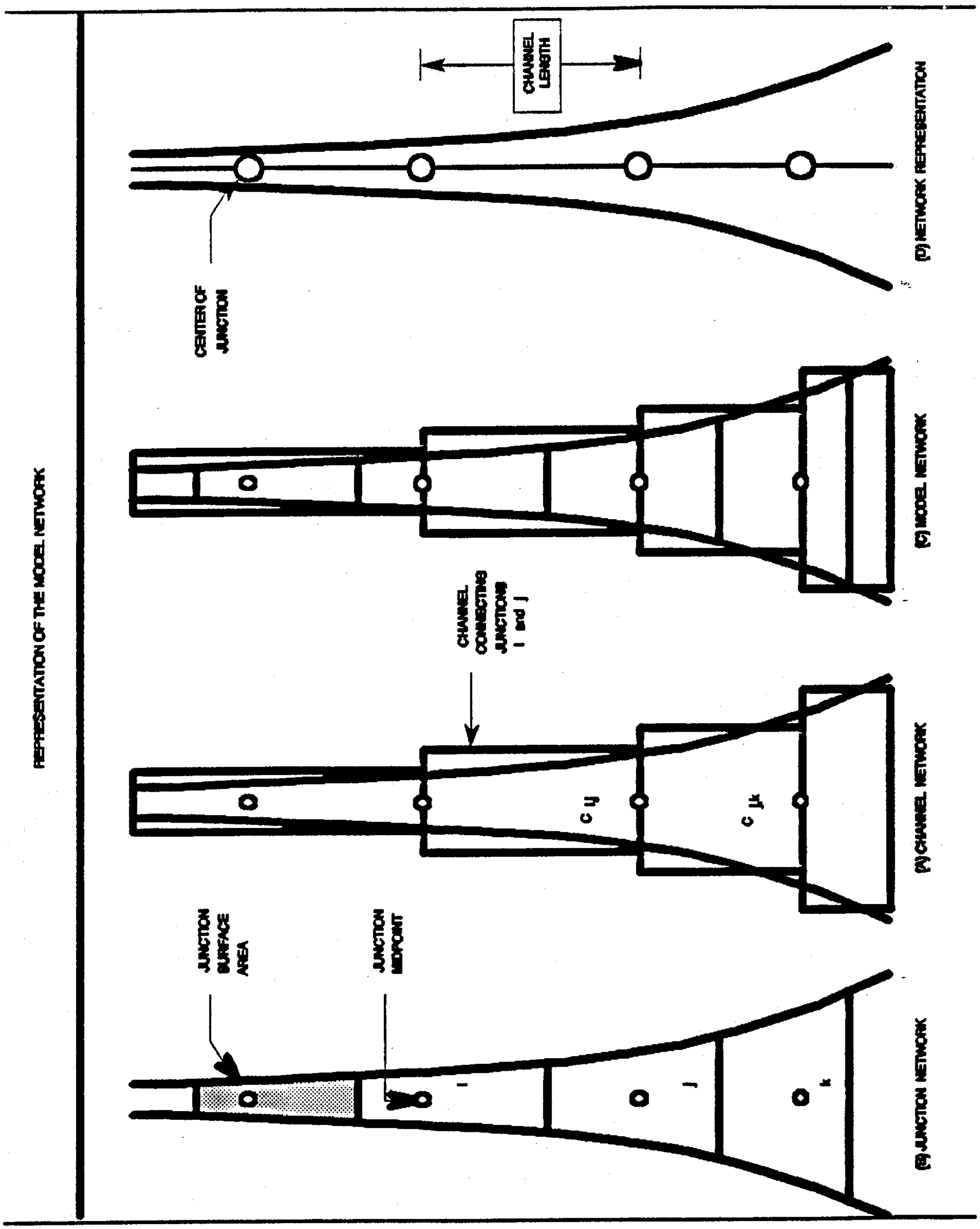



Figure 4-7. Representation of the link-node model network for WASP5 (Ambrose, 1991).

The link-node approach is not well-suited to application in Barnegat Bay because of several inflows and outflows. The tidal flows enter Barnegat Bay from the northern end through Point Pleasant Canal and from the east shore through Barnegat Inlet. A number of streams enter the Bay from the west shore. Furthermore, wind plays an important role in affecting the flow direction. Therefore, it is difficult to define a primary flow direction in Barnegat Bay.

The following equations describe this one-dimensional model which employs the concept of a single direction of flow:

- Mass Balance Equation for Water

$$\partial A / \partial t = -\partial Q / \partial x$$

where

$A$ = cross-sectional area, $m^2$
$Q$ = flow rate, $m^3/sec$

- Momentum Equation for Water

$$\partial U / \partial t = -U\, \partial U / \partial x + a_{g,\lambda} + a_f + a_{w,\lambda}$$

where

$\partial U / \partial t$ = the local inertia term, or the velocity rate of change with respect to time, $m/sec^2$
$U\, \partial U / \partial x$ = the Bernoulli acceleration, or the rate of momentum change by mass transfer; also defined as the convective inertia term from Newton's second law, $m/sec^2$
$a_{g,\lambda}$ = gravitational acceleration along the $\lambda$ axis of the channel, $m/sec^2$
$a_f$ = frictional acceleration, $m/sec^2$
$a_{w,\lambda}$ = wind stress acceleration along axis of channel, $m/sec^2$
$x$ = distance along axis of channel, m
$t$ = time, sec
$U$ = velocity along the axis of channel, m/sec
$\lambda$ = longitudinal axis

- General Mass Balance Equation

$$\partial / \partial t\, (A\, C) = \partial / \partial x\, (-U_x AC + E_x A\, \partial C / \partial x) + A\, (S_L + S_B) + AS_K$$

where

$A$ = cross-sectional area, $m^2$
$t$ = time, days

$U_x$ = longitudinal advective velocity, m/day
$E_x$ = longitudinal dispersion coefficient, $m^2$/day
$S_L$ = direct and diffuse loading rate, $g/m^3$ - day
$S_B$ = boundary loading rate (including upstream, downstream, benthic, and atmospheric), $g/m^2$ - day
$S_K$ = total kinetic transformation rate; positive is source, negative is sink, $g/m^3$ - day

### 4.4.2. MIT-DNM

For the same reason (one-dimensional nature) as WASP5, MIT-DNM is not appropriate for simulation of the circulation pattern in Barnegat Bay.

MIT-DNM is a one-dimensional transient water quality network model including nitrogen-cycle dynamics for rivers and estuaries (Harleman, et al., 1977). The uniqueness of this model is its sophisticated treatment of the nitrogen-cycle dynamics. The salinity component of the model has been applied to Delaware Estuary. In addition, this model was used to investigate the impact of a proposed flow diversion from the Manasquan River on the salinity intrusion in the estuary (Najarian and Harleman, 1989). It was also used to analyze the impacts of combined sewer overflow (CSO) discharge on the water quality of the lower Passaic River, which extends over a distance of 24.8 miles from Newark Bay to Great Falls in Paterson, New Jersey (Najarian and Harleman, 1989). In both latter two applications, no field data of tidal elevation and current velocity were used to verify the modeled results.

### 4.4.3 DYNLET

For the same reason (one-dimensional nature) as WASP5 and MIT-DNM, DYNLET is not appropriate for simulation of the circulation pattern in Barnegat Bay.

DYNLET is a one-dimensional hydrodynamic model (Amein and Cialone, 1994). The US Army Corp of Engineers (Seaburgh et al., 1995) has used it to simulate tidal elevations in Barnegat Bay. Tidal elevations at Bay Shore and Mantoloking were simulated well, but not at Waretown where two-dimensional effects are strong. Simulated current velocities were not verified by field conditions. DYNLET is not expected to simulate current velocities well due to the two-dimensionality of the Bay.

## 4.5. Two-Dimensional Models

### 4.5.1. TABS-2

- Introduction

Barnegat Bay is shallow and strong salinity or thermal stratification is not expected. Flow may primarily occur along the long axis of the bay and along the short axis of the bay. This is a classic two-dimensional situation. Thus, TAB-2 can be considered for simulating the circulation pattern of Barnegat Bay.

The U.S. Army Engineers Waterways Experiment Station (WES) released the Numerical Modeling System for Open Channel Flow and Sedimentation, TABS-2, in December 1985 (Thomas and McAnally, 1985) and has added features and upgrades annually since then. It is a two-dimensional vertically-averaged model. The three basic 2-D depth-averaged components of the system are as follows:

a. "A Two-Dimensional Model for Free Surface Flows," RMA2.
b. "Sediment Transport in Unsteady 2-Dimensional Flows, Horizontal Plane," STUDH.
c. "Two-Dimensional Finite Element Program for Water Quality," RMA4.

RMA2 is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. The finite element mesh for RAM2 is shown in Fig. 4-8. Friction is calculated with Manning's equation and eddy viscosity coefficients are used with side boundaries treated as either slip or static. The model has a marsh porosity option as well as the ability to automatically perform wetting and drying. Boundary conditions may be water-surface elevation, velocities, discharges, or tidal radiation.

The sedimentation model, STUDH, solves the convection-diffusion equation with bed source/sink terms. These terms are structured for either sand or cohesive sediments. Deposited material forms layers, and bookkeeping allows up to 10 layers at each node for maintaining separate material types, deposit thickness, and age. The code uses the same mesh as RMA2.

Salinity calculations, RMA4, are made with a form of the convection-diffusion equation which has general source-sink terms. Up to six conservative substances or substances requiring a decay term can be routed. The code uses the same mesh as RMA2. The model accommodates a mixing zone outside of the model boundaries for estimation of re-entrainment.

The following equations describe this two-dimensional model which considers flow in two directions:

- Mass Balance Equation for Water

$$\partial h/\partial t + h\,(\partial u/\partial x + \partial v/\partial y) + u\,\partial h/\partial x + v\,\partial h/\partial y = 0$$

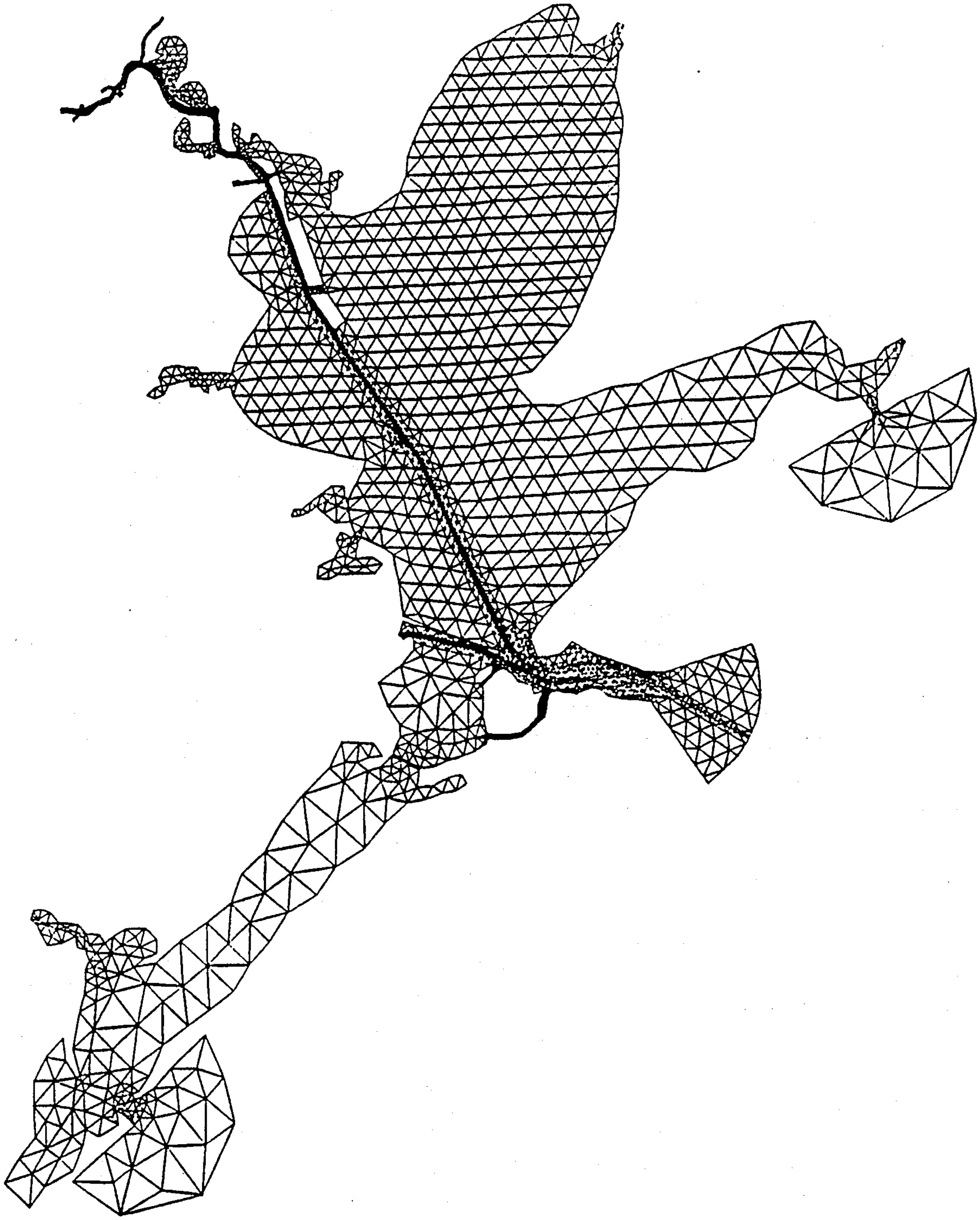


Figure 4-8. The finite element mesh for RMA2 (a component of two-dimensional model TABS-2) representing Galveston Bay. The mesh consisted of 3300 elements and 8200 nodes (Fast TAB manual).

- Momentum Equation for Water

$$h\partial u/\partial t + hu\,\partial u/\partial x + hv\,\partial u/\partial y - h/\rho\,(\epsilon_{xx}\,\partial^2 u/\partial x^2 + \epsilon_{xy}\,\partial^2 u/\partial y^2) + gh(\partial a/\partial x + \partial h/\partial x)$$

$$+ \frac{gun^2}{(1.486h^{1/6})^2}\,(u^2+v^2)^{1/2} - \xi V_a^2 \cos\psi - 2h\omega v \sin\phi = 0$$

$$h\,\partial v/\partial t + hu\,\partial v/\partial x + hv\,\partial v/\partial y - h/\rho(\epsilon_{yx}\,\partial^2 v/\partial x^2 + \epsilon_{yy}\,\partial^2 v/\partial y^2) + gh(\partial a/\partial y + \partial h/\partial y)$$
$$+ \frac{gvn^2}{(1.486h^{1/6})^2}\,(u^2+v^2)^{1/2} - \xi V_a^2 \sin\psi - 2h\omega u \sin\phi = 0$$

where

$h$ = depth
$u$, $v$ =velocities in the Cartesian coordinates
$x$, $y$, $t$ = Cartesian coordinates and time
$\rho$ = density of fluid
$\epsilon$ = eddy viscosity coefficient, for xx = normal direction on x-axis surface; yy = normal direction on y-axis surface; xy and yx = shear direction on each surface
$g$ = acceleration due to gravity
$a$ = acceleration of bottom
$n$ = Manning's n value
1.486 = conversion from SI (metric) to non-SI units
$\xi$ = empirical wind shear coefficient
$V_a$ = wind speed
$\psi$ = wind direction
$\omega$ = rate of Earth's angular rotation
$\phi$ = local latitude

- General Mass Balance Equation

$$h\,(\partial c/\partial t + u\,\partial c/\partial x + v\,\partial c/\partial y - \partial/\partial x\, D_x\,\partial c/\partial x - \partial/\partial y\, D_y\,\partial/\partial y - \sigma + kc) = 0$$

$h$ = water depth
$c$ = constituent concentration
$t$ = time
$u$, $v$ = velocity components
$D_x$, $D_y$ = turbulent mixing coefficients
$k$ = first order decay
$\sigma$ = source/sink of constituent

### 4.5.2. TRIM

The TRIM model can be considered for simulating circulation pattern in Barnegat Bay.

The TRIM (Tidal, Residual, Intertidal Mudflat) model (Cheng et al., 1993) uses a semi-implicit finite difference method for solving the two-dimensional shallow-wave equations. The gradient of the water surface elevation in the momentum equations and velocity divergence in the continuity equation are finite-differenced implicitly, the remaining terms are finite-differenced explicitly. The convective terms are treated using an Eulerian-Lagrangian method. The combination of the semi-implicit finite difference solution for the gravity wave propagation, and the Eulerian-Lagrangian treatment of the convective terms renders the numerical model unconditionally stable.

This numerical model is particularly suitable for applications to coastal plain estuaries and tidal embayments in which tidal currents are dominant, and tidally generated residual currents are important. The model has been applied to San Francisco Bay, California.

### 4.5.3. CLHYD

The CLHYD model can be considered for simulating circulation pattern of Barnegat Bay.

CLHYD, the Curvilinear Long Wave Hydrodynamic model, is a two-dimensional, depth-integrated model for studying tidal well-mixed bodies of water (Cialone, 1990). CLHYD can simulate flow fields induced by wind fields, river discharges, as well as tidal forcing. This model is formulated in terms of generalized curvilinear coordinates to accommodate non-orthogonal curvilinear (boundary-fitted) grids. A curvilinear grid system provides the flexibility needed to represent irregular boundaries accurately which in turn can lead to increased modeling efficiency. CLHYD was developed by streamlining a three-dimensional model (Sheng, 1986) into a 2-D model to minimize computations. It is a model in the Coastal Modeling System which is developed and maintained by Coastal Engineering Research Center at the Waterways Experiment Station (WES), U.S. Army Corps of Engineers.

### 4.5.4. WIFM

The WIFM model can be considered for simulating circulation pattern of Barnegat Bay.

The WES Implicit Flooding Model (WIFM) is a two-dimensional, depth-integrated model for computing tidal circulation and storm surge propagation. It is a model in the Coastal Modeling System which is developed and maintained by the Coastal Engineering Research Center at the Waterways Experiment Station (WES), U.S. Army Corps of Engineers. The model solves finite difference approximations of the Navier-Stokes (continuity and horizontal momentum) equations for the water surface displacement and the vertically integrated velocities. A rectangular grid system is used. The model was originally developed at WES for the simulation of tidal hydrodynamics at Great Egg Harbor and Corson Inlets, New Jersey (Butler, 1978). Tidal elevation and current velocities at various locations were simulated well. However, it was noted that the simulated flow pattern bayside of the Great Egg Harbor Inlet was quite irregular. Recent flow measurements at the same location did not reveal the flow irregularity (Psuty et al., 1993). Thus, before its application, the numerical scheme must be examined.

#### 4.5.5. HYDTID

HYDTID can be considered for simulating circulation pattern in Barnegat Bay.

HYDTID is a two-dimensional, hydrodynamic model which solves for depth-averaged current velocities, flows, and tidal heights and was developed by WES (Masch et al., 1977). It is a finite difference model and a rectangular grid system is utilized. This model was applied to Great Sound, New Jersey (Schuepfer et al., 1988). Tidal elevations and depth-averaged flow field were simulated reasonably well. However, this model is no longer maintained by WES.

### 4.6. Three-Dimensional Models

A survey of three-dimensional numerical estuarine models was conducted by Cheng and Smith (1990). 17 models were reviewed in their paper. Among them, three (King, 1985; Sheng, 1986; and Blumberg and Mellor, 1987) are reviewed briefly below.

#### 4.6.1. CH3D-WES and CE-QUAL-ICM

- Introduction

The basic model (CH3D) was developed by Sheng (1986) for WES but was extensively modified in its application to the Chesapeake Bay study (Johnson et al., 1993). These modifications have consisted of implementing different basic numerical formulations of the governing equations as well as substantial recoding of the model to provide more efficient computing. As its name implies, CH3D-WES makes hydrodynamic computations on a curvilinear or boundary-fitted plan-form grid. Physical processes impacting circulation and vertical mixing that are modeled include tides, wind, density effects (salinity and temperature), freshwater inflows, turbulence, and the effect of the earth's rotation.

An adequate representation of vertical turbulence is crucial to a successful simulation of stratification and destratification. A second-order turbulence model based upon the assumption of local equilibrium of turbulence is employed. The boundary-fitted coordinate feature of the model provides grid resolution enhancement necessary to adequately represent deep navigation channels and irregular shoreline configurations of the flow system. The curvilinear grid also permits adoption of accurate and economical grid schematization software. The solution algorithm employs an external model in which the free surface elevation and depth-averaged currents are computed as input to the internal mode, which provides the 3-D solution.

CH3D-WES does not contain an adaptive gridding algorithm, therefore there is no means to allow for flooding and drying of low-lying areas.

CE-QUAL-ICM is a three-dimensional, time-variable, eutrophication model. CE-QUAL-ICM incorporates 22 state variables that include physical properties, multiple forms of algae, carbon, nitrogen, phosphorous, and silica, and dissolved oxygen. The model is a part of a larger package that includes a three-dimensional hydrodynamic model and a benthic-sediment diagenesis model.

Use of CH3D-WES and CE-QUAL-ICM as a depth-averaged two-dimensional model is demonstrated through its application to Indian River and Rehoboth Bay, Delaware (Cerco et al., 1994). CH3D-WES has been applied to simulate three-dimensional hydrodynamics of Chesapeake Bay (Johnson et al., 1993) and New York Bight (Scheffner et al, 1994). CE-QUAL-ICM has been applied to model the eutrophication process in Chesapeake Bay (Cerco and Cole, 1993). The grid system used for Chesapeake Bay is shown in Fig. 4-9.

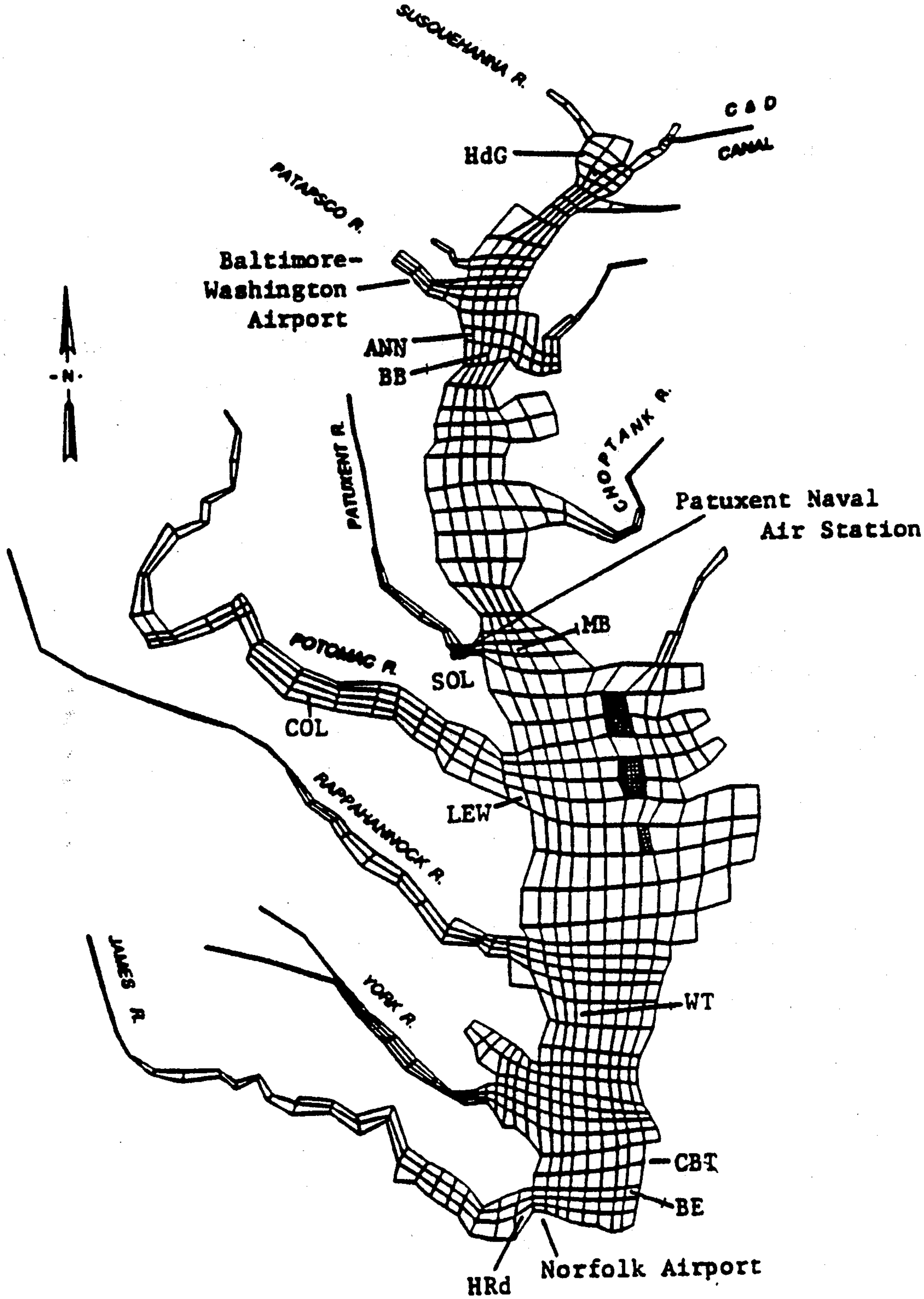



Figure 4-9. Three-dimensional model CE-QUAL-ICM planform grid of Chesapeake Bay and gage locations (Johnson et al., 1993).

The following equations describe this three-dimensional model which considers flow in three directions:

- Mass Balance Equation for Water

$\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0$

- Momentum Equation for Water

(1) $\partial u/\partial t + \partial u^2/\partial x + \partial uv/\partial y + \partial uw/\partial z = fv - 1/\rho_o\, \partial p/\partial x + \partial/\partial x\, (A_H\, \partial u/\partial x)$
$+\partial/\partial y\, (A_H\, \partial u/\partial y) + \partial/\partial z\, (A_v\, \partial u/\partial z)$

(2) $\partial v/\partial t + \partial uv/\partial x + \partial v^2/\partial y + \partial vw/\partial z = -fu - 1/\rho_o\, \partial p/\partial y + \partial/\partial x\, (A_H\, \partial v/\partial x)$
$+\partial/\partial y\, (A_H\, \partial v/\partial y) + \partial/\partial z\, (A_v\, \partial v/\partial z)$

(3) $\partial p/\partial z = -\rho g$

- Equation for Temperature

$\partial T/\partial t + \partial uT/\partial x + \partial vT/\partial y + \partial wT/\partial z$

$= \partial/\partial x\, (K_H\, \partial T/\partial x) + \partial/y\, (K_H\, \partial T/\partial y) + \partial/\partial z\, (K_v\, \partial T/\partial z)$

- Mass Balance Equation for Salinity

$\partial S/\partial t + \partial uS/\partial x + \partial vS/\partial y + \partial wS/\partial z$

$= \partial/\partial x\, (K_H\, \partial S/\partial x) + \partial/\partial y\, (K_H\, \partial S/\partial y) + \partial/\partial z\, (K_v\, \partial S/\partial z)$

- Equation of State

$\rho = \rho\, (T, S)$

Where
$(u, v, w)$ = velocities in $(x, y, z)$ directions
$t$ = time
$f$ =Coriolis parameter defined as $2\Omega \sin \phi$ where
$\Omega$ = rotational speed of the earth
$\phi$ = latitude
$\rho$ = density
$p$ = pressure
$A_H$, $K_H$ = horizontal turbulent eddy coefficients
$A_v$, $K_v$ = vertical turbulent eddy coefficients

g = gravitational acceleration
T = temperature
S = Salinity

Note that the CH3D model assumes that the hydrostatic pressure distribution adequately describes vertical distribution of fluid pressure, i.e., it assumes that vertical water accelerations are small in comparison with gravitational acceleration, which is the same assumption as that for the two-dimensional depth-averaged model. In this sense, CH3D is not a truly three-dimensional model, it may more properly be described as a vertically multi-layered two-dimensional model, or as a layered version of the three dimensional model.

### 4.6.2. TABS-MD

TABS-MD is a complete multi-dimensional numerical modeling system suitable for use in solving many problems involving hydraulic behavior of rivers, reservoirs, wetlands, estuaries, and bays. Examples of past use include predicting flow patterns and erosion in a river reach constricted by a cofferdam, evaluation of sedimentation rates in a deepened navigation channel (both rivers and estuaries), determining the impact of flood control structures on salinity intrusion, and defining flow and sedimentation impacts to wetlands. TABS-2, a two-dimensional model, described above is an earlier version of TABS-MD.

In the TABS-MD modeling system, RAM-10 is a three-dimensional hydrodynamics model, which was originally developed by King (1985), SED-8 is a three-dimensional sediment transport model, and RMA-9 is a three-dimensional water quality model (solids and D.O.). RAM-6 is a multi-layered version of the three-dimensional hydrodynamic model.

From NYCDEP's Catalog of Hydrodynamic and Water Quality Models of New Harbor Vicinity (NYCDEP, 1993), 3 out of 17 listed models were developed by Lawler, Matusky & Skelly Engineers, Pear River, New York. All LMS's models are based on the TABS-MD modeling system. One of LMS's recent applications of TABS-MD is for water quality modeling of combined sewer overflow effects on Newtown Creek, New York (Apicella et al., 1993).

### 4.6.3. ECOM-si

ECOM-si (Estuarine, Coastal, and Ocean Model, semi-implicit) is a three-dimensional circulation model, which was initially developed by Blumberg and Mellor (1987). One recent application of this model was for Massachusetts Bay (Signell et al., 1993). It seems that the current version of ECOM-si (Signell et al., 1993) is similar to the current version of CH3D-WES described above (Scheffner et al., 1994) in terms of simulation of the three-dimensional circulation pattern.

From NYCDEP's Catalog of Hydrodynamic and Water Quality Models of New York Harbor Vicinity (NYCDEP, 1993), 14 out of 17 listed models were developed by HydroQual, Inc., Mahwah, New Jersey.

### 4.7. Summary

A review of models of various dimensions provides background for their consideration in representing the conditions in Barnegat Bay. The simpler the model, the more general the representation of the conditions. Major assumptions and applicabilities of models of various dimensions are listed in table 4-2.

In the zero-dimension models, the bay can be treated as either a very large box or a series of boxes in which average conditions are determined. Although simple, these models can represent a general condition, and that has value. However, these models lack temporal or spatial variability and are not appropriate for detailed analysis.

The one-dimensional models permit the incorporation of flow rates and diffusion, thereby relating values of variables to a directional gradient. The general assumption is that the flows are in the direction from the drainage basin through the bay and through the inlet. Whereas this approach is an advance on the zero-dimension models, because gradients and diffusion are considered, the limitation of a single directional gradient is a handicap. It is likely that wind drives some of the circulation in Barnegat Bay across the short axis in its horizontal plane, thus complicating the direction of circulation.

The two-dimensional models incorporate the use of flows and gradients along the long axis and short axis of the Bay. This is a major consideration because they can simulate the downstream gradients that are largely produced by the land based discharges (long axis) and the ocean-produced/wind produced cross-bay gradient(short axis).

A three dimensional model may be needed if gradients exist in the vertical plane in the Bay in addition to the gradients in the long and short axes directions. Vertical stratification or inadequate mixing, and vertical current, would generate the need for a three-dimensional model. Limited stratification and vertical current could be handled with a layered version of the three-dimensional model.

Of the several categories of models that exist it is likely that a two-dimensional depth-averaged model will be adequate to represent the conditions present in Barnegat Bay. However, as additional field data are generated, there may be situations recorded which can only be represented by the more sophisticated three-dimensional models.

## 5.0 Design of Field Collection Plan

### 5.1. Initial Selection of a Circulation Model for Field Data Collection Design

The field data collection plan was designed based on the data requirements for a potential numerical circulation model. From the cursory review of the existing circulation models, the shallowness of the Bay, and the budget constraint, it was initially determined that a two-dimensional depth-averaged model would be appropriate to serve as the base for the field data collection plan design. The two-dimensional depth-averaged model could include TABS-2, TRIM, and the two-dimensional version of CH3D-WES/QUAL-ICM. If a two-dimensional depth-averaged model were selected as the basis, the recording of the value of the variable at one representative location in the vertical direction for each sampling point would meet the minimum field data requirements, thus reducing the sampling costs.

Different models have different field data requirements for their execution, calibration, and verification depending mostly on the level of their sophistication. All estuarine circulation models simulate current velocity and tidal elevation, and most simulate salinity also. Some estuarine circulation models simulate temperature additionally. The envisioned circulation model for Barnegat Bay will include these four variables. Thus, values of current velocity, tidal elevation, salinity, and temperature were measured in the field.

### 5.2. General Data Requirements to Drive a Numerical Circulation Model

To simulate the circulation pattern, information at the boundary of the computational domain will be required. These boundaries include the water/water boundary, land/water boundary, water/bed boundary, and air/water boundary. The data requirements at these boundaries are described below:

- Water/water boundary: This boundary is also called an open boundary. Either water depth or flow velocity will be needed at this boundary. Data on salinity and temperature at this boundary will also be needed.

- Land/water boundary: It is a common practice that the flow velocity normal to the land/water boundary be set to zero, and that flow velocities parallel to the land/water boundary are set by the log law of wall. Momentum of the ground water seepage can be neglected, but the input of freshwater from the land might need to be considered for Barnegat Bay due to its possible significance in dilution of sea water.

- Water/bed boundary: Shear stress on the bed has already been incorporated in the governing equation, therefore, no additional boundary condition is needed. However, freshwater input from the bed might need to be considered for this Barnegat Bay.

- Air/water boundary: Information of wind shear stress on water surface will be needed.

Information on heat flux across the water/air interface will also be needed.

With the above field data, a numerical circulation model can be executed. However, without information within Barnegat Bay, the simulated circulation pattern of Barnegat Bay can not be calibrated and verified.

## 5.3. Data Requirements to Calibrate and Verify a Numerical Model

All numerical circulation models require input of some coefficients which can not be or may be difficult to measure. In the hydrodynamic component of the two-dimensional depth-averaged model (e.g., RMA2 in TABS-2), there are two types of coefficients which need to be calibrated. One is the Manning's roughness coefficient (n). Although the bottom roughness height is fixed, due to the complex velocity profiles resulting from combined actions of tide, winds, and river inflows, the Manning's coefficient is expected to vary widely. Another variable needed is the eddy viscosity ($\epsilon_{xx}$, $\epsilon_{xy}$, $\epsilon_{yx}$, and $\epsilon_{yy}$). The viscosity can be input directly or be calculated by a closure model. If a closure model is used, other coefficients will be needed. In the mass transport component of the two-dimensional depth-averaged model (e.g., RMA4 in TABS-2), dispersion coefficients ($D_X$ and $D_Y$) have to be calibrated. The circulation pattern within the Bay will change depending the values of the coefficients used, thus one set of field data within the Bay is needed to calibrate the coefficients used.

The calibrated coefficients should be applicable under all field conditions. Thus, at least one more set of the field data within the Bay under a condition significantly different from that used for the calibration should be collected for verification of the calibrated coefficients.

## 5.4. Conceptual Field Data Collection Plan for Barnegat Bay

### 5.4.1. Data collection at boundaries of the Bay

Because wind is probably the dominant driving force for the circulation in Barnegat Bay, and the wind condition is not regular, it was necessary to collect the long term data at the boundaries. Furthermore, a numerical model is normally started with an assumed field condition within the Bay, thus, a set of long term boundary data are required to wipe out the effect of the assumed initial condition. One month was chosen for the long-term data collection.

### 5.4.2. Data Collection within the Bay

The data within the Bay are needed to calibrate and verify the numerical circulation model. There are two types of data which were collected. One is the long term data, e.g., one month, at certain points, to provide information about temporal variation. Another type is short term data, e.g., one tidal cycle, at certain transects to provide information about spatial variation.

Detailed implementation of the conceptual plan is described along with information on the collected field data.

## 6.0 Instruments and Their Deployment

Various instruments were used to obtain the different types of data required to present a clear picture of the hydrodynamics of Barnegat Bay. Some of the instruments were placed to gather data at a point within Barnegat Bay through an extended period. These instruments had recording data loggers for subsequent downloading and analysis. Other instruments collected data through the water column and/or along bay transects. Some of these had data loggers, others had analog displays that were recorded into notebooks.

The combination of point data through various time periods and at numerous locations was planned to provide measurement through tidal cycles during several climate seasons. Table 6-1 provides a summary of the different types of instruments used and the data they provided in temporal and spatial scales.

TABLE 6-1 INSTRUMENTATION AND DATA COLLECTED

| Name of Instrument | Data Collected | Time Domain | Spatial Domain |
|---|---|---|---|
| S-4 Current Meter | Current Speed/Direction<br>Temperature<br>Salinity | Long Term Data<br>- One to five weeks<br>- Three periods (Winter, Spring, Summer) | - Data obtained at 6 different locations throughout bay.<br>- Data represents conditions at a single point approximately 2.5 feet from bottom. |
| Marsh McBirney Model 511 Bi-directional Current Meter | Current Speed/Direction | Short Term Data<br>- Over a tidal cycle | - Data obtained along three different East/West transects throughout bay.<br>- Data represents conditions in the water column (vertical distribution) at a single location. |
| Marsh McBirney Model 201 Uni-directional Flow Meter | Current Speed/Direction | Short Term Data<br>- Over a tidal cycle | - Data obtained along three different East/West transects throughout bay.<br>- Data represents conditions in the water column (vertical distribution) at a single location. |
| Seacat SBE 19-03 Conductivity, Temperature, Depth Recorder (CTD) | Salinity<br>Temperature<br>Depth | Short Term Data<br>- Over a tidal cycle | - Data obtained along East /West and North/South bay transects<br>- Data represents conditions in the water column (vertical distribution) at a single location. |
| SIGMA Model 950 Area Velocity Flow Meter | Depth (Tidal Elevation) | Long Term Data<br>- Over many tidal cycles | - Data represents change in level at a single location.<br>- Data augments USGS tidal gauge data. |
| PAROS Pressure Transducer | Depth (Tidal Elevation) | Long Term Data<br>- Over many tidal cycles | - Data represents change in level at a single location.<br>- Data augments USGS tidal gauge data. |
| ADCP | Current Speed/Direction | Short Term Data<br>- Over a tidal cycle | -Data obtained along four East/West and North/South bay transects.<br>- Data represents both vertical and horizontal distributions (contour) |

## 6.1. S-4 Instrument

The S-4 Current Meter, manufactured by InterOcean systems, Inc., measures the true magnitude and direction of horizontal current motion in fresh or salt water. It can be deployed up to 1000 meters deep. During operation an electromagnetic field is created by the instrument. When water flows through the field a potential gradient (voltage) is produced proportional to the water velocity past the sensor. The voltage is sensed by two pairs of titanium electrodes located about the central plane of the instrument. The data obtained by the S-4 is stored internally in 64K RAM memory. From this memory, data is retrieved through an RS232C port to a personal computer.

All electronics and power supplies required by the S-4 are contained within a compact 10 inch diameter sphere made of durable, high strength, dimensionally stable, corrosion proof plastic. Power is supplied by 6 alkaline "D" cells. The S-4 is ideal for low current regimes like Barnegat Bay because of its low threshold and low noise level. The grooved surface of the S-4 allows for stable hydrodynamic characteristics ensuring linearity stability. There are no mechanical movements or protrusions from the instrument to interfere with the water flow pattern. An internal compass provides heading information to reference the current direction to magnetic north.

Connection to a mooring is made by means of a titanium load bearing shaft which runs vertically through the center of the S-4. The S-4's were moored in Barnegat Bay with an in-line system using 80 lb concrete block anchors (Fig 6-1). Additional weights brought the total weight of the anchor to 120 lbs. A 1/8 inch plastic coated steel cable was used with marine shackles and galvanized cable ties to connect the S-4 to the concrete block. A polypropylene line was used to connect a subsurface buoy to the S-4 to maintain a vertical orientation. The subsurface buoy provided 13 lbs of lift in water. The S-4 weighed approximately 5 lbs in water. The S-4 was set to maintain a two and a half foot distance from the bottom. An additional 50 foot plastic coated steel cable was used to attach the concrete block to selected Intracoastal Waterway channel marker pylons permanently imbedded into the sediment. The Coast Guard granted permission to make this connection for the purposes of security and locating the instrument for retrieval. This precluded the use of a surface marker. The S-4 was located far enough away from the aid-to-navigation, approximately 20 feet, to prevent any magnetic interference or error-inducing current fluctuations. The S-4 at Barnegat Inlet was originally moored to a channel marker buoy, but because the buoy was not fixed and could cause entanglement with the concrete block cable, the S-4 concrete block used during June/July was fixed to the shoreline using a 250 foot cable.

Up to five S-4s were deployed simultaneously in Barnegat Bay during the research project. Four S-4s were rented from the University of Delaware and one was rented from the New Jersey Marine Science Consortium. The instruments were deployed at the three water-water (open) boundaries of the bay and three interior points for various periods of time. The instruments were moored adjacent to the following navigational aids:

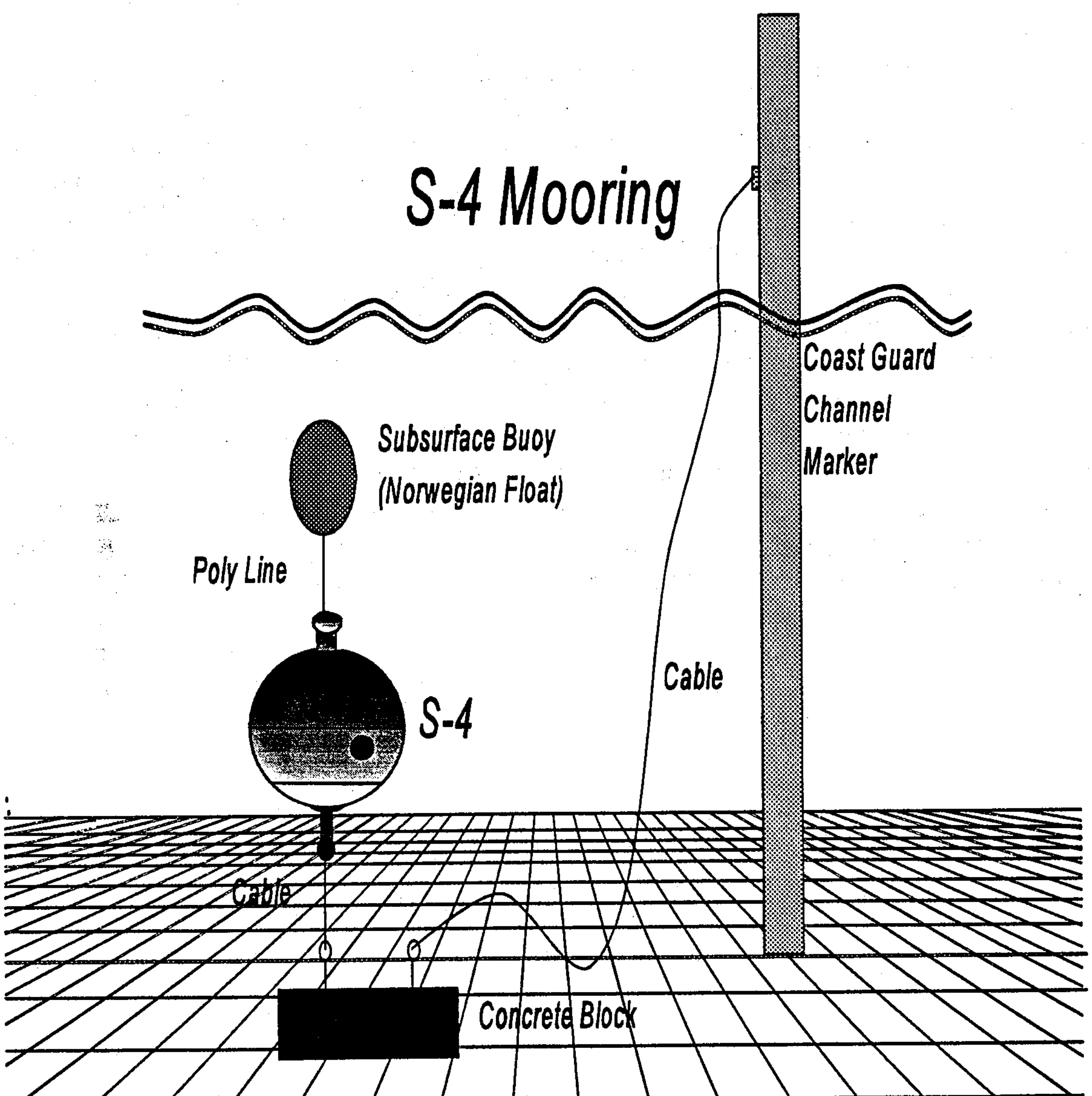



Figure 6-1. Method used to moor the S-4 instrument

| Bay Location | Closest Navigational Aid | Location Type |
|---|---|---|
| Mantoloking | #15 | Northern open boundary |
| Silver Bay | #22 | Interior point |
| Cedar Creek | #40 | Interior point |
| Barnegat Inlet | Inlet Buoy/Shoreline | Eastern open boundary |
| Loveladies Harbor | #49A | Interior point |
| Surf City | #62 | Southern open boundary |

The S-4s provided current speed, current direction, temperature, and salinity. See Fig.6-2 for an example of recorded current magnitude and direction. It can be seen that the current magnitude peaks approximately four times a day and current direction changes twice a day; this is typical of a semi-diurnal tide. Figure 6-3 shows recorded time variations of salinity and temperature. Salinity and temperature peak about twice a day typical of a semi-diurnal tide. The S-4 from the Marine Science Consortium additionally provided water depth with the addition of an internal pressure transducer. The S-4s used during the January data collection were programmed to turn on every 15 minutes and to remain on for 5 minutes. During the 5-minute period the instrument recorded a vector-averaged current velocity twice and conductivity/temperature/depth once. The S-4s used for the rest of the data collection were programmed to turn on every 10 minutes and to remain on for 3 minutes. During the 3-minute period the instrument recorded one vector averaged current velocity and one temperature/conductivity/depth measurement. These data collection frequencies maximized memory space and battery life for approximately a one-month deployment. The clocks for the group of instruments were synchronized to ensure simultaneous data collection.

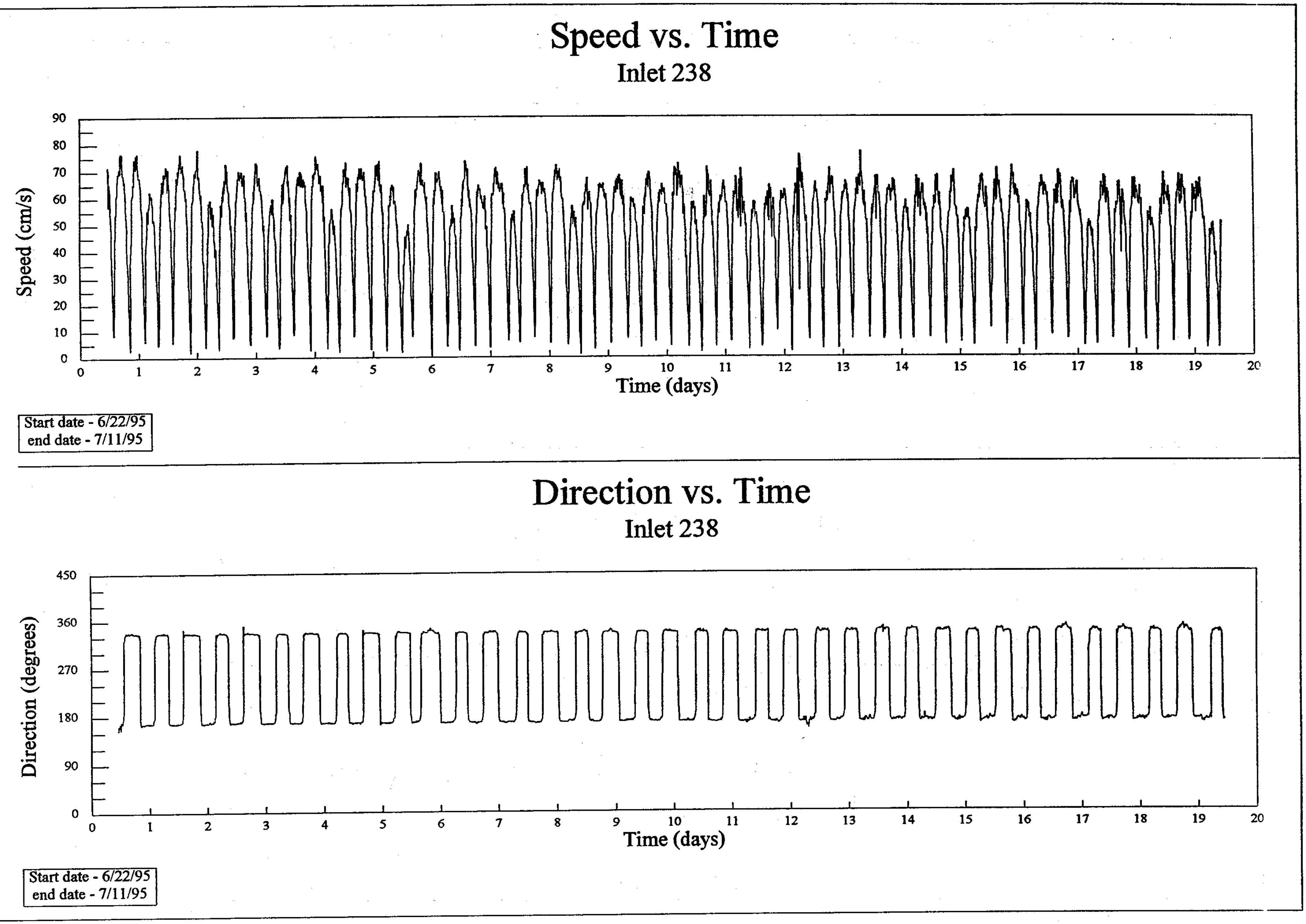



Figure 6-2. An example of current speed and direction output recorded by an S-4 instrument at Barnegat Inlet

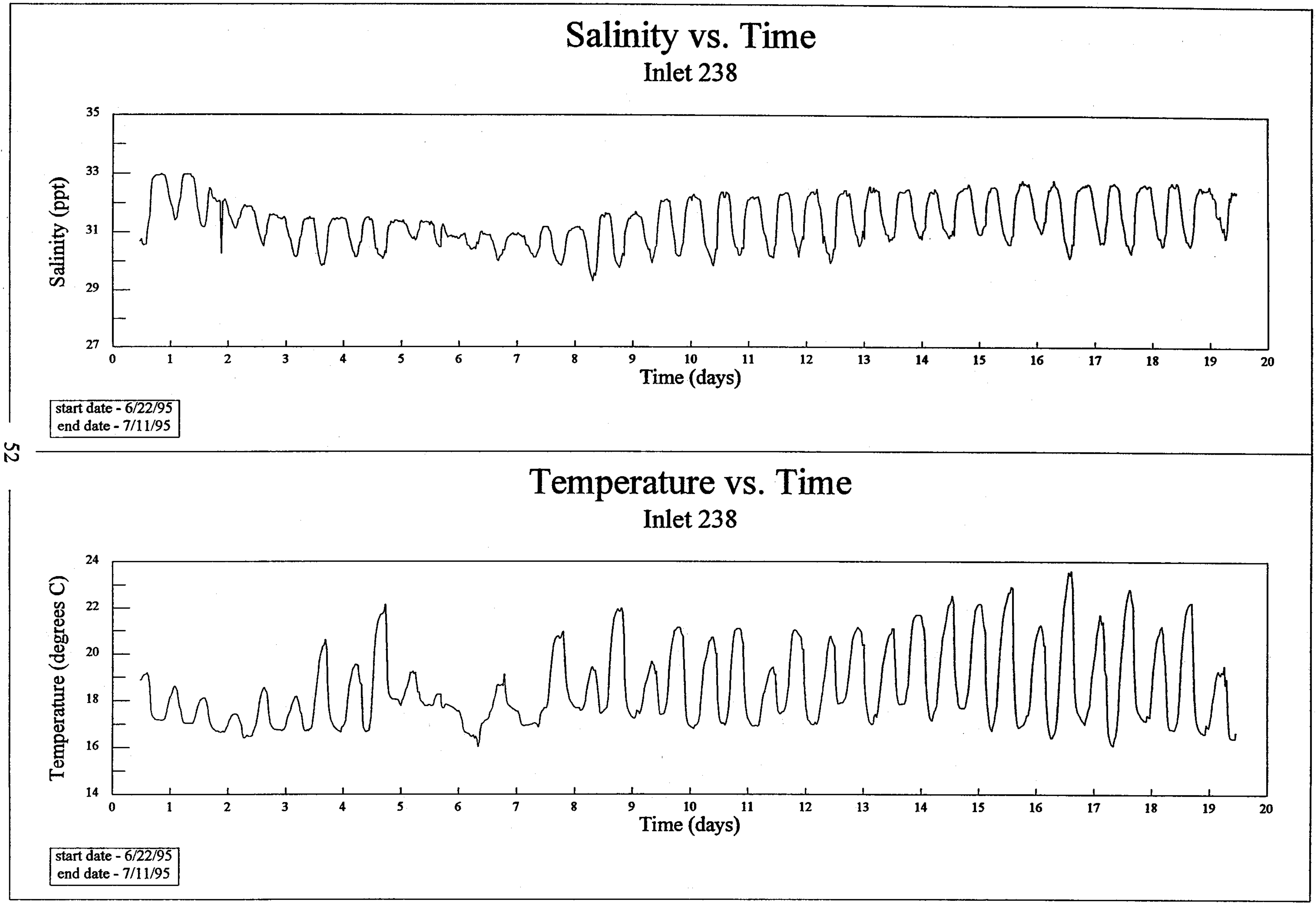



Figure 6-3. An example of temperature and salinity variation recorded by an S-4 instrument at Barnegat inlet

## 6.2 Marsh McBirney Meters.

### 6.2.1 Model 511 Electromagnetic Water Current Meter.

The Model 511 current meter is a general purpose instrument consisting of a transducer probe with cable and a signal processor housed in a portable case. The instrument senses water flow in a plane normal to the longitudinal axis of the electromagnetic sensor. The sensor is based on the Faraday principle of electromagnetic induction which states that a conductor (water) moving in a magnetic field (generated from within the flow probe) produces a voltage that is proportional to the velocity of the water. Panel analog displays provide the visual observation of flow information. Flow information is outputted as water velocity components along the X-axis and Y-axis of the electromagnetic sensor. The 511 flowmeter is powered by two rechargeable 6 volt Gel-Cell batteries contained in the portable case. The case is approximately 12 inches x 9 inches x 10 inches tall, and weighs about 15 pounds. The probe is 1.5 inches in diameter. The standard cable length is 20 feet.

The full scale output range of water velocity components measured along the X and Y axes of the electromagnetic sensor is +300 to - 300 cm/sec. The output range used to take readings in Barnegat Bay was +60 to -60 cm/sec. The outputs of the instrument are passed through low pass filters with a time constant of one second, providing running averages of 10 one-second readings.

The probe incorporates a mounting sting which provides mechanical support and probe orientation (Fig 6-4). Mounting the probe consisted of mating it with a suitably-machined PVC pipe and applying screw type hose clamps near each end of the overlapping section.

### 6.2.2 Model 201 Portable Water Flow Meter.

The Model 201 is a portable water flowmeter that measures velocity in one direction from an electromagnetic sensor placed in a conductive liquid. The velocity measurement is output on an analog panel meter as ft/sec. The unit consists of a case containing the electronics, a sensor, and sensor cable. The power supply is 6 D-size batteries.

When the flow approaches the sensor from directly in front, then the direction of the flow, the magnetic field, and the sensed voltage are mutually perpendicular to each other, and the voltage will then represent the velocity of the flow at the electrodes on the sensor.

### 6.2.3 Deployment.

The Marsh McBirney meters were deployed as shown in Figure 6-5. The meter's probe was fixed to a rotatable PVC pipe that could also change elevations to obtain a velocity profile. The pipe could be rotated to maximize the direction of flow for the uni-directional meter. The probes position was adjusted by hand from a boat. Meter panel readings and visual depth readings were recorded on the boat. The Marsh McBirney profiles were taken at specific transects that crossed Barnegat Bay. Measured sample velocity distributions at a specific time are shown in Figure 6-6. Marsh McBirney transects were taken at Mantoloking, Silver Bay, Cedar Creek, and Surf City.

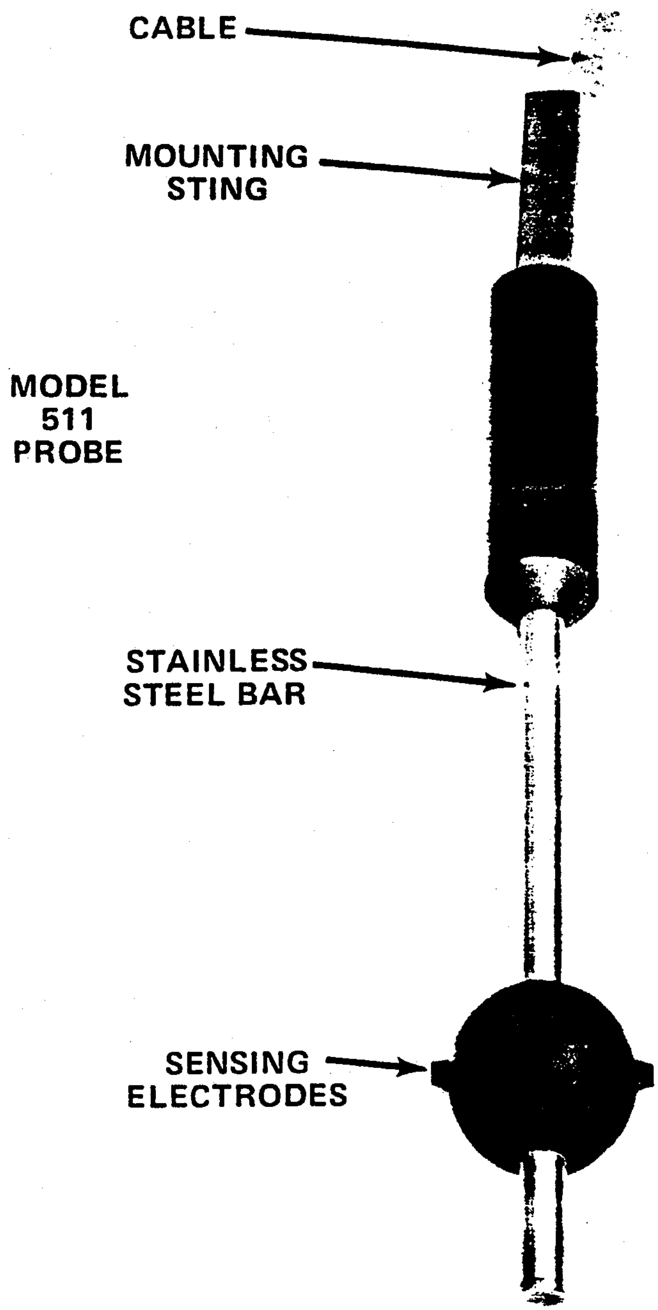



Figure 6-4. Marsh-McBirney current meter bi-directional transducer probe.

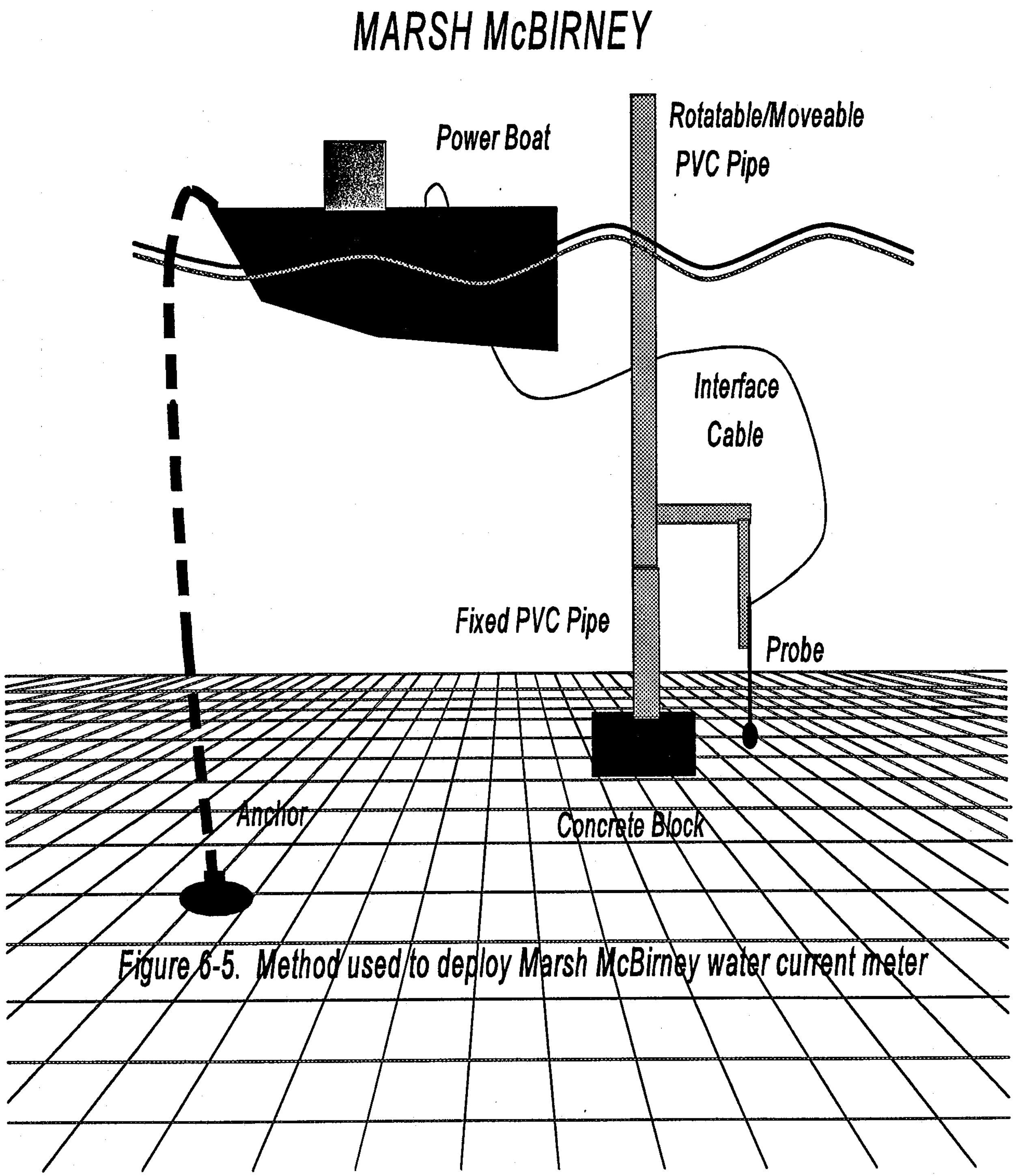



Figure 6-5. Method used to deploy Marsh McBirney water current meter

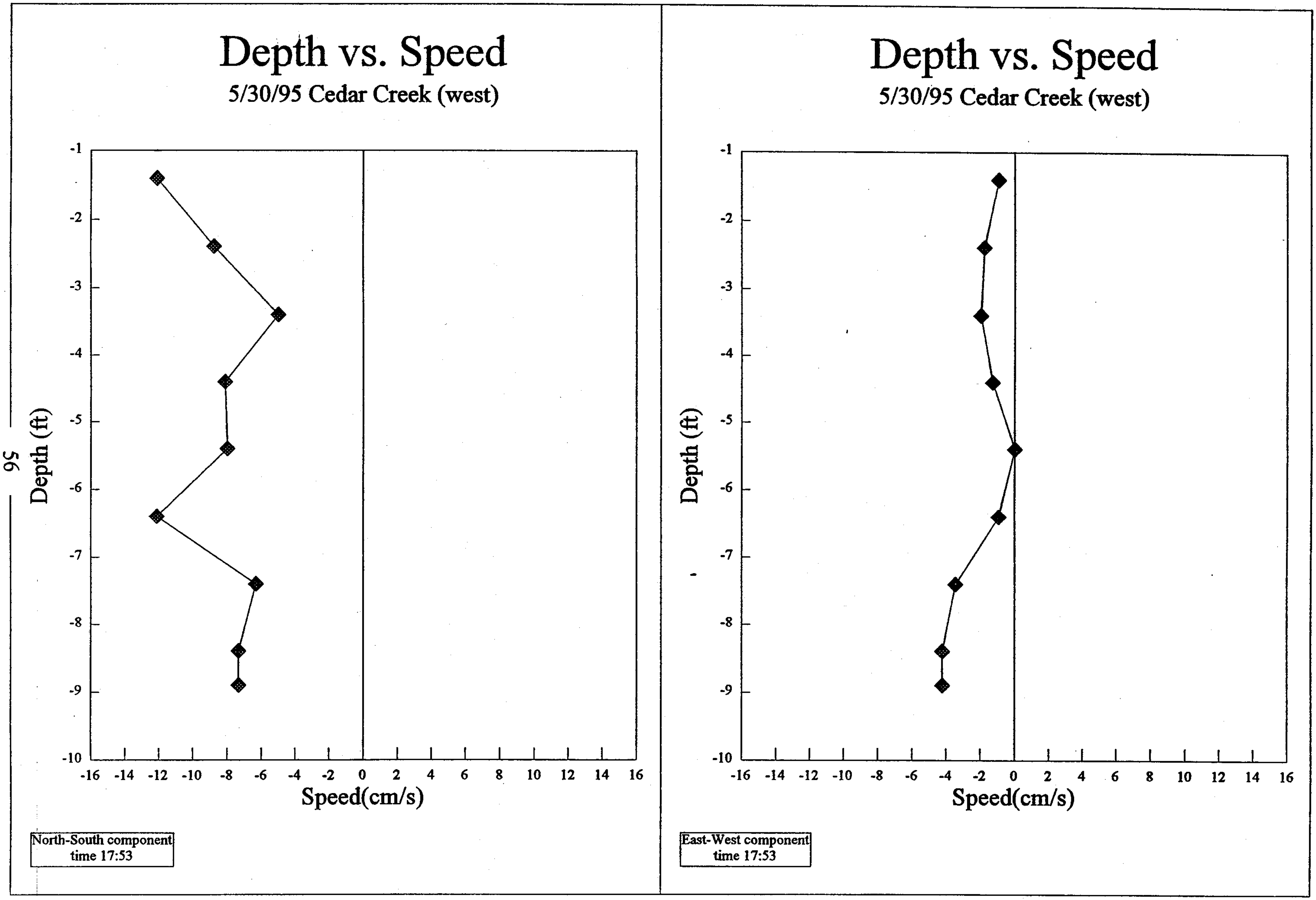



Figure 6-6. Current velocity vertical profiles in N/S and E/W components recorded by Marsh McBirney current meter at Cedar Creek

## 6.3. Seacat SBE 19-03 Conductivity, Temperature, Depth Recorder (CTD).

The CTD measures electrical conductivity, temperature, and pressure (semiconductor strain-gauge pressure transducer) in marine and fresh water environments to depths up to 6800 meters. The CTD was operated in the profiling mode which provides vertical profiles of the measured parameters. The sampling rate can be varied between twice a second to once every 4-minutes in half second increments. The CTD used was set at twice per second because of the shallow waters in Barnegat Bay. The CTD is self-powered and self-contained. Six alkaline batteries provide 48-hour operation in profiling mode. A 128K solid-state memory allows 3.0 hours of recording while sampling at two scans per second. The optimum profiling speed is about one meter per second. The CTD is intended for obtaining down-cast data and is deployed with the sensors at the bottom of the instrument.

The CTD was used by attaching a polypropylene line and physically downcasting it from a boat at approximately .75 meters per second. See Figure 6-7 for CTD instrument and actual deployment. See Figure 6-8 for sample CTD data, vertical temperature and salinity profiles respectively. CTD casts were performed in conjunction with the ADCP transects (Loveladies, Cedar Creek, Toms River, Silver Bay) and Marsh McBirney profiles.

## 6.4 Tidal Gages

### 6.4.1 SIGMA Model 950 Area Velocity Flow Meter.

The SIGMA 950 was used to measure water level for tidal information. It can measure up to a maximum depth of 10 feet at an accuracy of +/- .01 foot. The SIGMA 950 utilizes the bubbler method of level measurement. A small probe containing both level and velocity sensors is affixed in a flow stream. A small amount of air is continuously pushed through the sensor and bubbles are emitted slowly out the side of the sensor housing. The back-pressure pushing against the bubbling air changes in proportion to the liquid level in the flow stream. The SIGMA 950 reads this pressure and converts it to a depth reading.

The SIGMA 950 was deployed from a dock at two locations at Surf City; a marina and a yacht club. The locations were chosen based on availability of power and security of the instrument. The probe was simply fixed on top of a weighted cage and placed in the water (Fig. 6-9). Long term data records portray the tidal variations (Fig. 6-10).

### 6.4.2 Pressure Transducer

The 2100-AS-17 PAROS Pressure Transducer (PT) and Sea Data Model 1255B-27 data logger measures differences in pressure caused by the varying weight of the column of water over the PT during a tidal cycle. The PT consists of a pressure sensor housed in a PVC cylinder. The internal lines are filled with oil between a flexible membrane connected to an external port. At one end is an analog output plug that connects to a designated channel in the data logger via a connecting cable. The range of the PT is 0 to 100 Psia. As the pressure sensor responds to

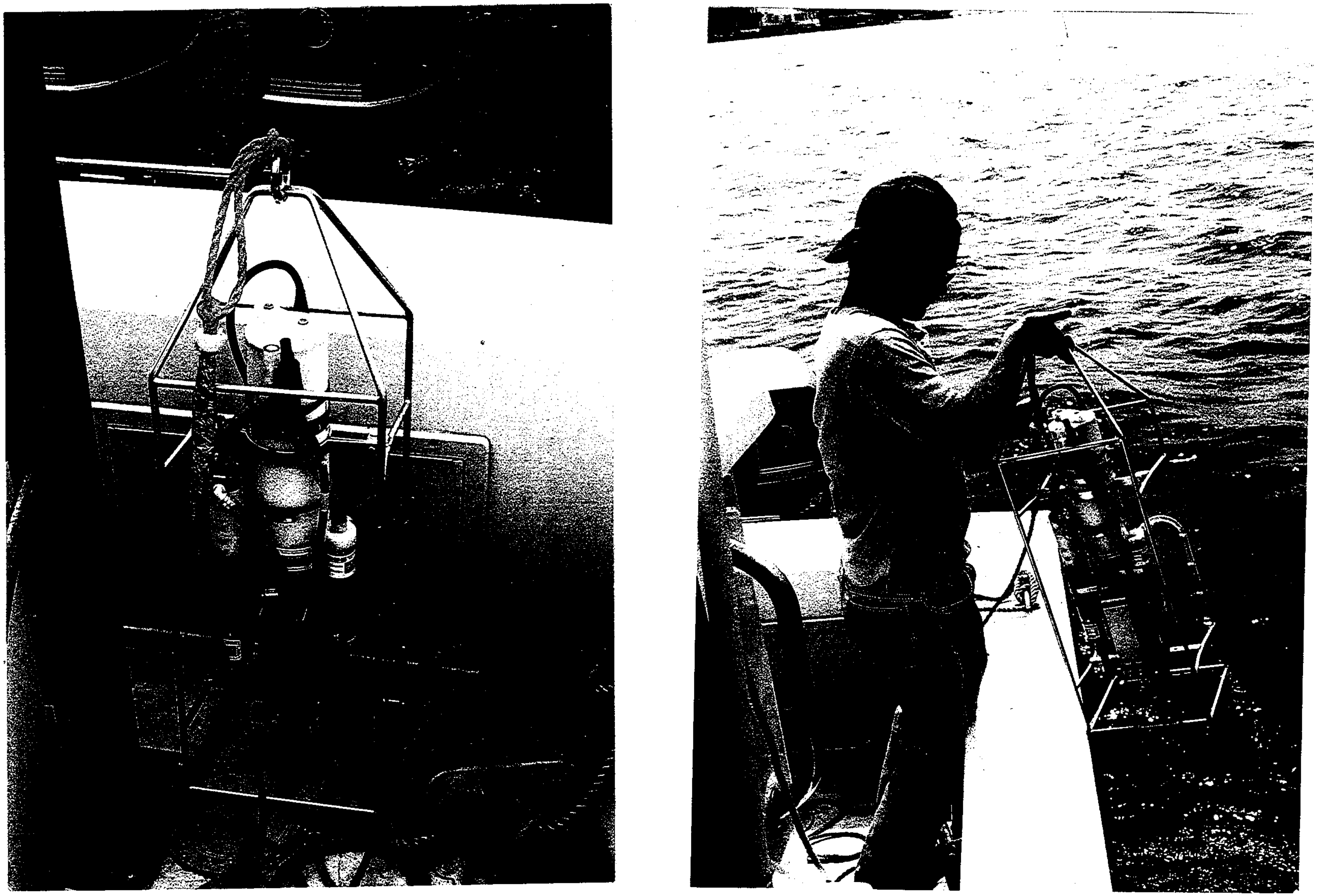


Figure 6-7. CTD instrument:
Left- CTD in cage, water intake located at bottom of cylinder.
Right- CTD records data as it is lowered through water column.

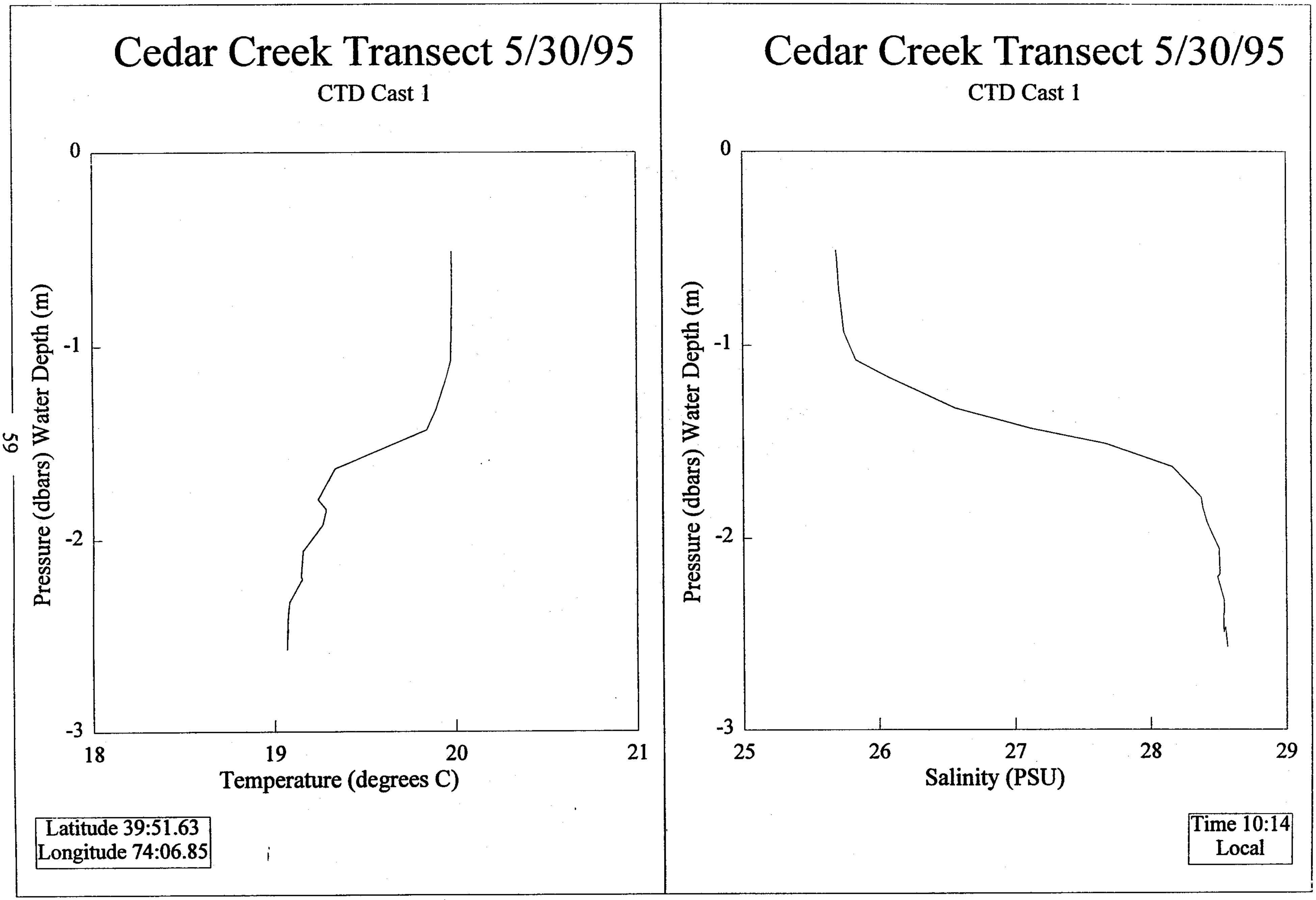



Figure 6-8. An example of CTD temperature and salinity vertical profiles at Cedar Creek

# SIGMA 950

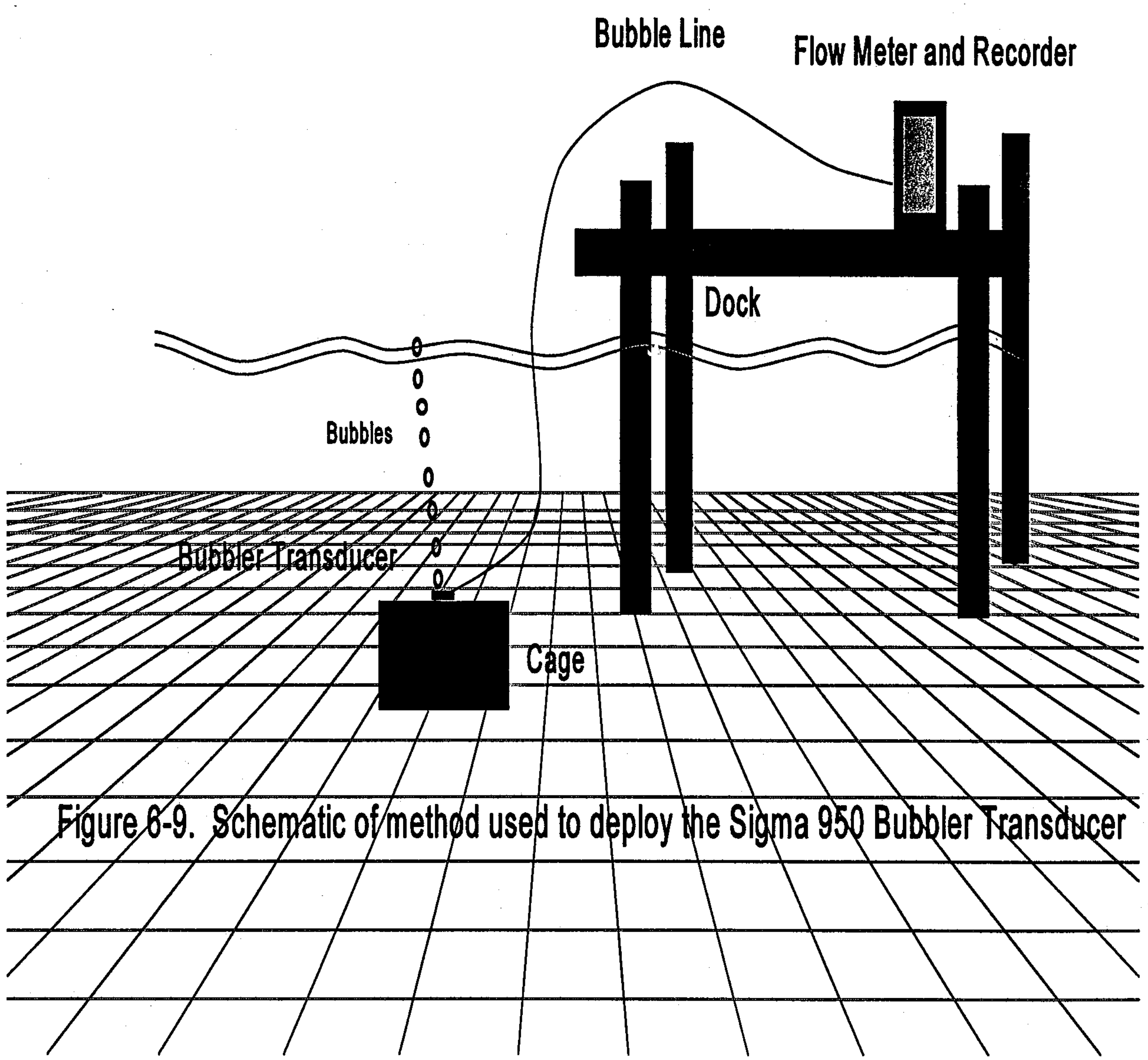



Figure 6-9. Schematic of method used to deploy the Sigma 950 Bubbler Transducer

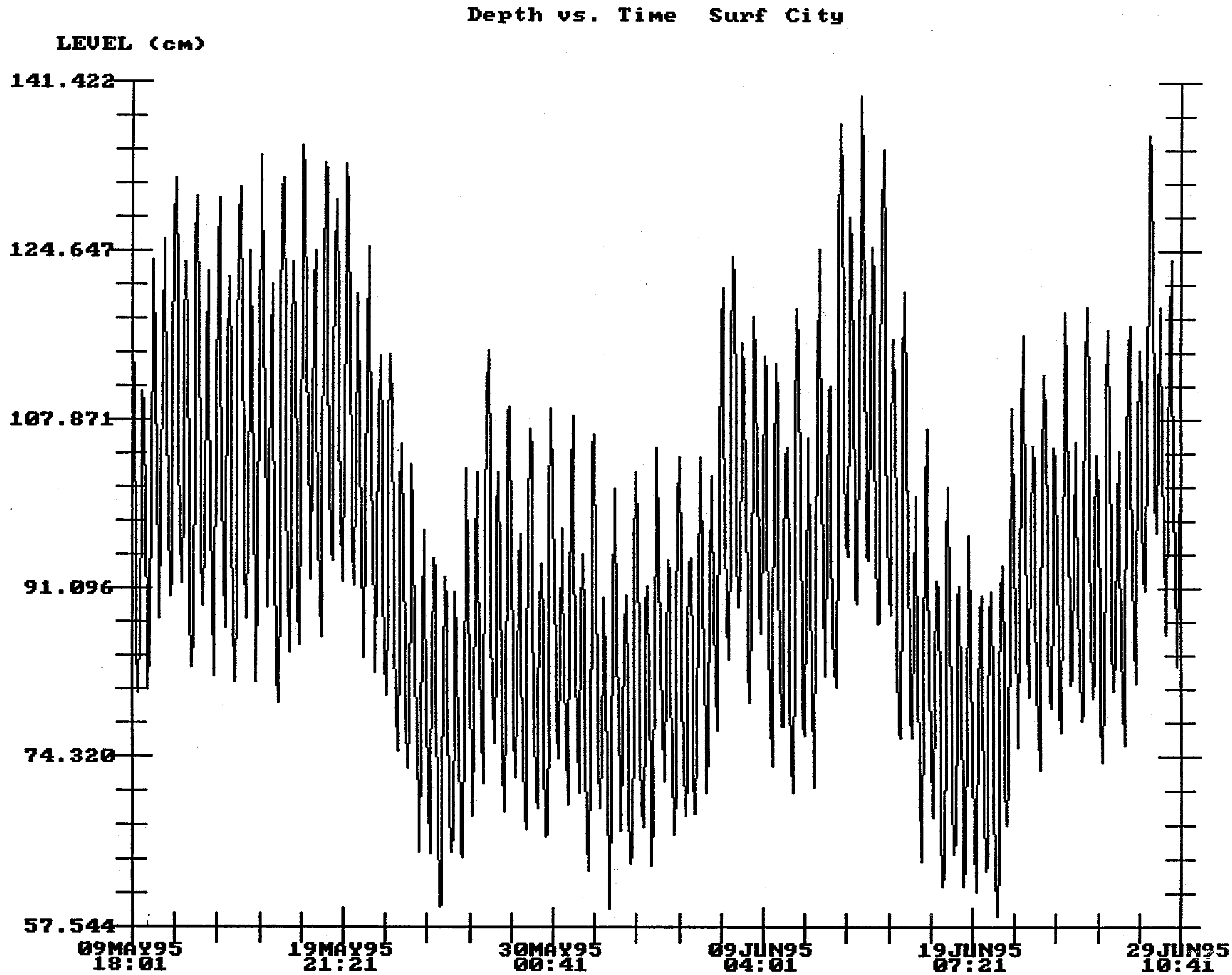



Figure 6-10. An example of water surface elevation at Surf City recorded by the SIGMA 950 instrument.

changes in water surface displacement it transmits a voltage to the data logger. Power for the PT, 6 Volts, is supplied through the data logger. The data logger can operate from its 12-volt rechargeable internal battery or direct AC power. The data logger can store up to 17 channels of input data, including one channel which is dedicated to the PT signal. The data logger receives an analog voltage signal from the PAROS pressure transducer and then the analog signal is converted into a digital format before being stored in the data logger memory. Later, the data is downloaded to a PC and transformed into a measure of water depth. The PT was deployed similarly to the SIGMA 950. A malfunction in the data logger caused the instrument to obtain a limited amount of data.

### 6.5 ADCP.

The acoustic doppler current profiler (ADCP) measures current velocity based on the doppler shift when the acoustic beam interacts with particles flowing in the water. The U.S. Army Corps of Engineers personnel made ADCP measurements to assist Rutgers' research. During the operation, the ADCP acoustic beam tube was mounted on the side of the boat (Fig. 6-11) which emits pulsed acoustic beams downward through the water column and receives the reflected beams. The acoustic beam is reflected differently by the solid bottom than by particles in the water column, thus, the bottom boundary is also detected. The data are received by the computer and can be observed directly on a computer screen (Fig. 6-11). Vertical velocity profiles can be obtained while the boat is moving. Thus, within a relatively short period of time, depending on boat speed typically less than 3 knots, a velocity contour for a cross-section can be obtained (Fig. 6-12).

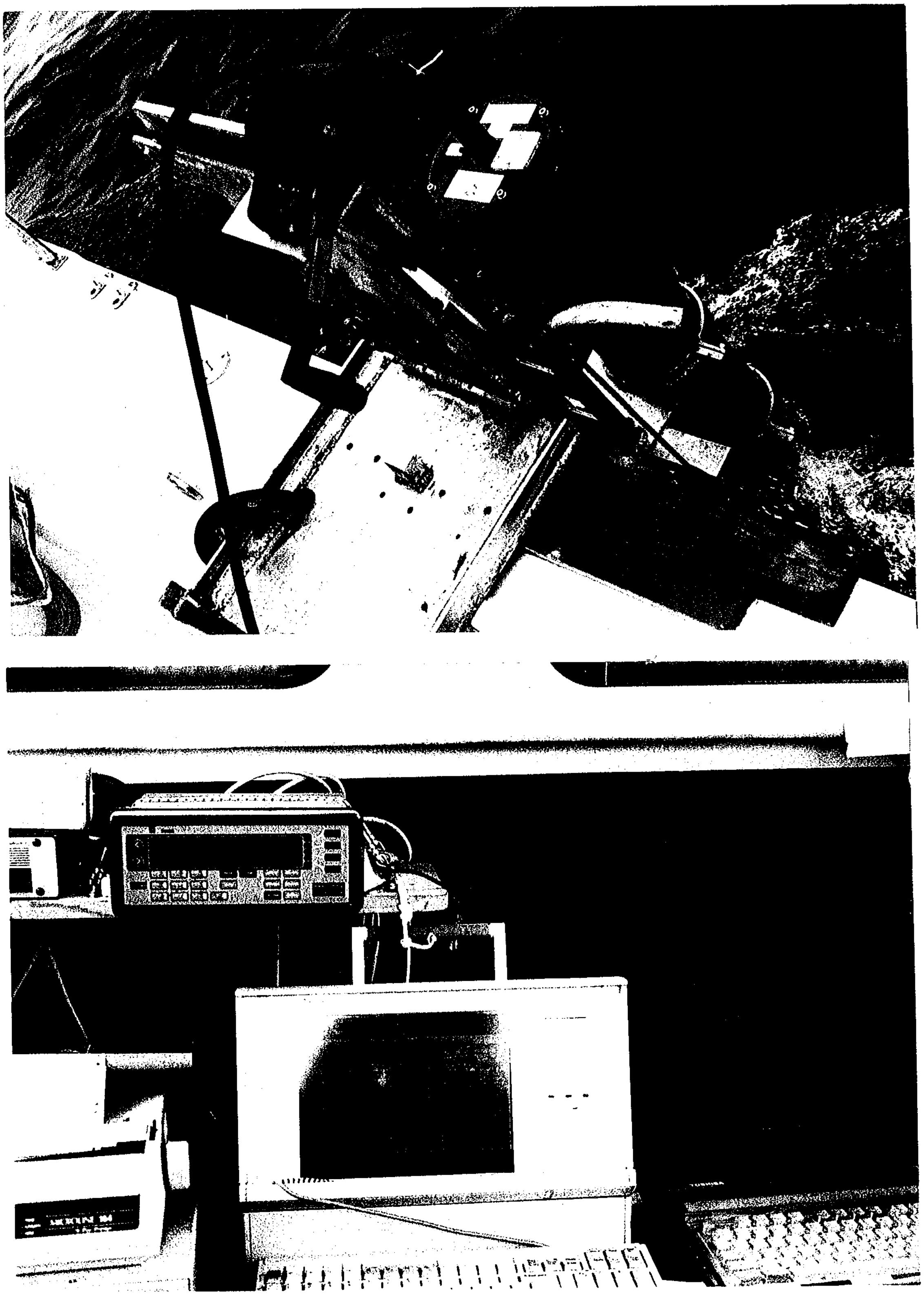


Figure 6-11. Acoustic Doppler Current Profiler:
Top- ADCP mounted on side of boat, recording along transect.
Bottom- Real time CRT display of vertical distribution of current velocity.

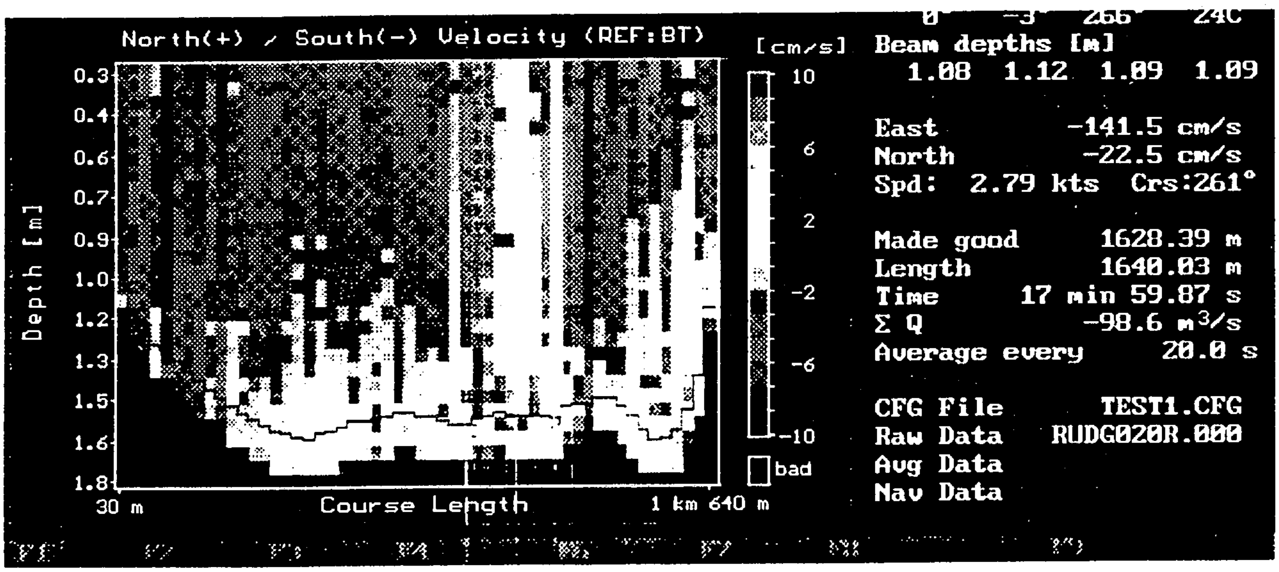



Figure 6-12. An example of the velocity contour along a transect in Barnegat Bay recorded by the ADCP.

## 7.0 Spatial and Temporal Field Data Assemblages

### 7.1. Instrument Locations

The distribution of instrument locations is shown in Fig. 7-1. Instruments were deployed during three time periods, December, 1994-January, 1995, May-June, 1995, and June-July, 1995.

#### 7.1.1. Data collection at boundaries of the Bay

- Water-Water (Open) Boundaries

There are several significant open boundaries for this Bay. Protocol of data collection at these boundaries is described below:

Barnegat Inlet: National Ocean Survey has a tidal gage in operation at the Coast Guard Station adjacent to the inlet. A portable S-4 metering system (field data logger with probes to simultaneously measure the environmental variables of current velocity [in two directions], conductivity, and temperature) was installed in the Oyster Creek Channel adjacent to Sedge Islands. Velocity profiles were measured using the ADCP at nearby transects. This transect served as the eastern open boundary of the Bay.

Mantoloking Transect: The U.S.G.S. has a long term tidal gage at this location. A portable S-4 was also installed. In addition, a vertical velocity profile was measured at the transect using a Marsh-McBirney current velocity meter. This transect served as the northern boundary of the Bay. The Bay Head - Manasquan Canal (Point Pleasant Canal) was initially considered as the northern boundary of the Bay. The new location was selected to take advantage of the available long-term tidal gage. Furthermore, the Metedeconk River located to the north of the boundary is not expected to play an important role in terms of the major circulation pattern for the Bay.

Surf City Transect: A portable tidal gage with data logger and an S-4 was installed. In addition, the vertical velocity distribution was measured at the transect using a Marsh-McBirney current velocity meter. This transect served as the southern boundary of the Bay. The Manahawkin Causeway was initially considered as the southern boundary of the Bay. However, the new transect was selected after examining the topography of the bed which shows a flow diversion south of the Surf City Transect. Such a complex flow situation is not a good section for use as a boundary for the numeral circulation model unless many data collection points are set up along the transect.

Toms River: There is an existing water level gage operated by U.S. Geological Survey in Toms River. The flow rate interpreted from the measured water level will be used as a boundary condition for the circulation model. USGS water temperature data and conductivity data will also be used. A velocity profile was measured by using ADCP at the transect.

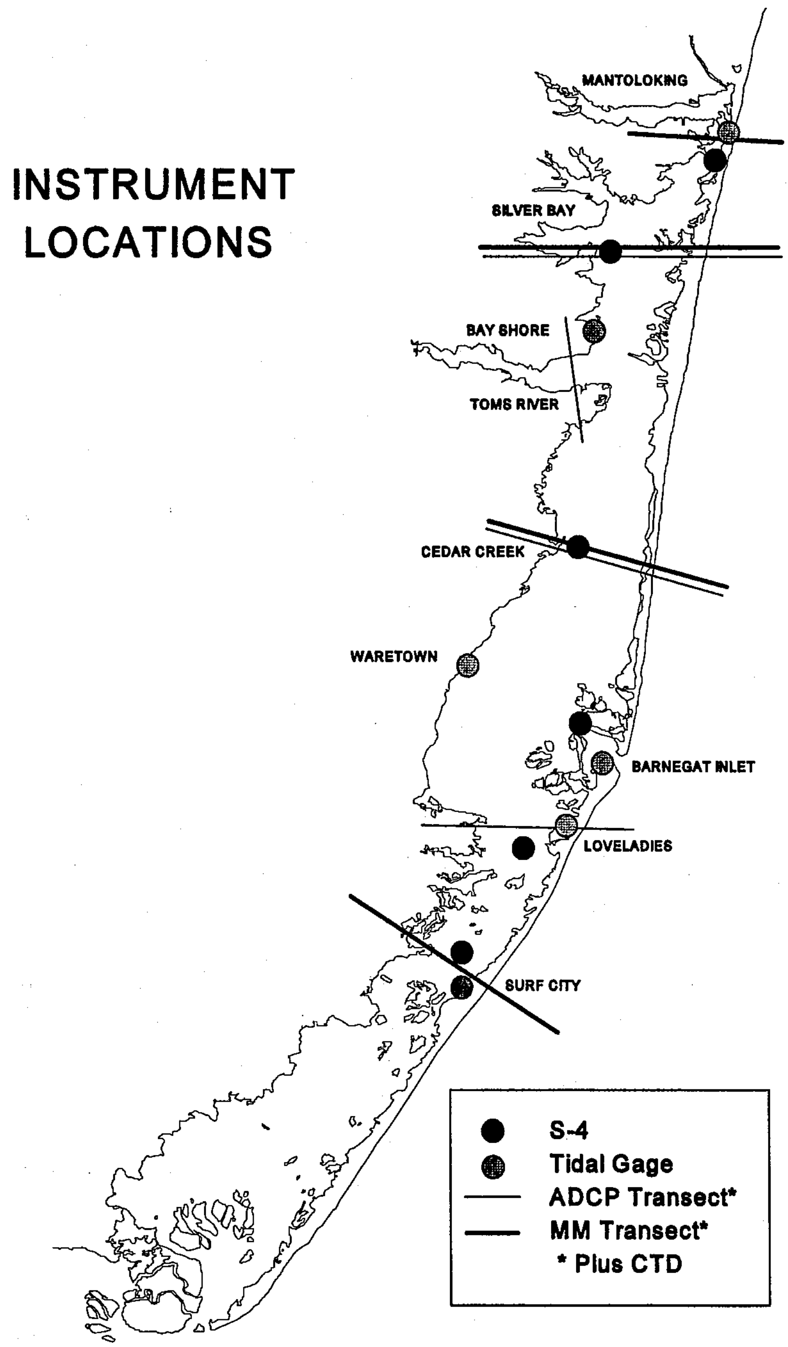



**Figure 7-1. Distribution of data collection points and transects in Barnegat Bay**

Cedar Creek Transect: No water level gage is in operation in this creek. Although this source is minor, hydrologic analysis, using rainfall information, can be conducted to obtain the flow rate. Values of temperature and salinity can also be estimated.

Forked River and Oyster Creek: The GPU Nuclear Corporation is taking water from Barnegat Bay via Forked River and discharging cooling water to Barnegat Bay via Oyster Creek. The information on flow rate and temperature can be obtained from GPU Nuclear Corporation. Salinity of the flow can be estimated.

Other Streams and Creeks and Watershed of Direct Runoff: Water from these sources are insignificant and can be neglected in studying the circulation pattern.

- Land-Water Boundary:

There might be some groundwater seepage to the Bay at the land-water boundary. The long-term monitoring wells in this region penetrate into the aquifer which bypasses the Bay, thus these recordings can not be used to estimate the rate of the direct groundwater seepage. A three-dimensional model has recently been conducted to simulate the groundwater pattern by U.S.G.S. (Nicholson, 1995). Before measurements of direct groundwater seepage into the Bay are made, U.S.G.S.'s groundwater model can be applied for the first order of approximation.

- Water-Bed Boundary:

A direct measurement of seepage rate from the bed to the Bay is desirable. However, at this stage of the study, U.S.G.S.'s groundwater model results have to used.

- Air-Water Boundary:

Meteorological data are available from GPU Nuclear Corporation, from the Rutgers Marine Field Station in Tuckerton, and from the Weather Station at Atlantic City.

### 7.1.2. Data Collection within the Bay

The data within the Bay are needed to calibrate and verify the numerical circulation model. There are two types of data which were collected. One is the long term data, e.g., one month, at certain points, to provide information about temporal variation. Another type is short term data, e.g., one tidal cycle, at certain transects provide information about spatial variation.

There exist three tidal gage stations within the Bay, in addition to the station located in Mantoloking at the northern boundary and the one at Barnegat Inlet. Tidal elevation data from these three stations, namely, Waretown, Bayshore (Toms River), and Loveladies, can be used to calibrate and verify the circulation model. These tidal records are continuous and of long term.

Three recording stations were established within the Bay to gather continuous data of water surface elevation, current velocity, conductivity, and temperature for one month in winter, one in spring, and the last in summer. One station was placed outside Cedar Creek (south of Toms River) to record information in the middle portion part of the Bay. A portable tidal gage and S-4 were used at this location. Another mid-Bay site was selected to be near Loveladies to take advantage of the existing tidal gage and to record information within the southern part of the Bay. An S-4 was placed at this location to record current velocity, conductivity, and temperature. A third within-bay site was placed outside Silver Bay in the northern portion of the Bay. An S-4 was placed at this location. For calibration and verification of the circulation model, more stations within the Bay are better.

Velocity profiles, salinity profiles, temperature profiles, and water surface elevation were measured at all three interior transects for a time period of one tidal cycle or less. The CTD (Conductivity-Temperature-Depth) metering system was used to record conductivity and temperature profiles. The Marsh-McBirney current velocity meters and ADCP were used for measuring the current velocity profiles.

These profiles at three transects, along with the long-term data gathered within the Bay and at the boundaries, form a complete set of data for calibration and verification of a two-dimensional depth-averaged numerical circulation model.

The following sections summarize the types of field data collected during three time periods. Actual data are presented in Appendices:

## 7.2 December/January Data Set

### 7.2.1 S-4 Data

| Locations | Serial # | Parameter | Time Period | Source |
|---|---|---|---|---|
| Cedar Creek | 822 | Vel/Dir/Sal/T | 1120 1/9/95 - 1505 1/13/95 | Rutgers |
| Surf City | 822 | Vel/Dir/Sal/T | 1100 12/23/94 - 1600 12/29/94 | Rutgers |
| Mantoloking | 137 | Vel/Dir/Sal/T | 1335 1/9/95 - 0735 1/26/95 | Rutgers |
| Loveladies | 733 | Vel/Dir/Sal/T | 1105 12/29/94 - 1120 1/14/95 | Rutgers |
| Surf City | 819 | Vel/Dir/Sal/T | 0850 1/9/95 - 1250 1/26/95 | Rutgers |
| Barnegat Inlet | 820 | Vel/Dir/Sal/T | 1050 1/9/95 - 1005 1/26/95 | Rutgers |

### 7.2.2 Tidal Gage Data

| Location | Type | Parameter | Time Period | Source |
|---|---|---|---|---|
| Surf City | Press Trans | Water Level | 1453 12/23/94 - 1013 12/23/94 | Rutgers |
| Surf City | Press Trans | Water Level | 1321 01/19/95 - 0621 01/23/94 | Rutgers |
| Barnegat Inlet | | Water Level | Available | NOS |
| Loveladies | | Water Level | Available | USGS |
| Waretown | | Water Level | Available | USGS |
| Bay Shore | | Water Level | Available | USGS |
| Mantoloking | | Water Level | Available | USGS |

### 7.2.3 Meteorological Data

| Location | Parameters | Time Period | Source |
|---|---|---|---|
| Atlantic City | Wind Speed/Dir, Temp, etc. | Available | NWS |
| Tuckerton | Wind Speed/Dir, Temp, etc. | 12/94 - 01/95 | Rutgers |
| Oyster Creek GPU Nuclear | Wind Speed/Dir, Temp, etc. | Available | GPU |

### 7.2.4 River Flow Data

| Location | Parameter | Time Period | Source |
|---|---|---|---|
| Toms River | River Flow | Available | USGS |

## 7.3 May/June Data Set

7.3.1 S-4 Data

| Location | SN | Parameter | Time Period | | Source |
|---|---|---|---|---|---|
| Cedar Creek | 137 | Vel/Dir/Sal/T/Depth | 1000 5/12/95 | - 1330 5/17/95 | Rutgers |
| Mantoloking | 239 | Vel/Dir/Sal/T | 1150 5/4/95 | - 1810 6/1/95 | Rutgers |
| Surf City | 238 | Vel/Dir/Sal/T | 0820 5/4/95 | - 0810 6/2/95 | Rutgers |
| Cedar Creek | 237 | Vel/Dir/Sal/T | 1400 5/24/95 | - 0930 6/2/95 | Rutgers |
| Silver Bay | 237 | Vel/Dir/Sal/T | 1200 5/4/95 | - 1130 5/24/95 | Rutgers |

7.3.2 Marsh McBirney Data

| Location | Type | Parameter | Time Period | Source |
|---|---|---|---|---|
| Cedar Creek (east) | Uni-direction | Vel/Dir vs Depth | 0810-1909 5/30/95 | Rutgers |
| Cedar Creek (west) | Bi-direction | Vel/Dir vs Depth | 0915-1831 5/30/95 | Rutgers |
| Silver Bay | Bi-direction | Vel/Dir vs Depth | 1352-1754 6/1/95 | Rutgers |

7.3.3 CTD Data

Cedar Creek Transect 5/30/95 Salinity/Temperature Profile Rutgers

| Cast # | Time | Location |
|---|---|---|
| 0 | 0959 | center |
| 1 | 1014 | west |
| 2 | 1025 | center |
| 3 | 1035 | east |
| 4 | 1141 | west |
| 5 | 1145 | center |
| 6 | 1151 | east |
| 7 | 1239 | west |
| 8 | 1244 | center |
| 9 | 1249 | east |
| 10 | 1419 | west |
| 11 | 1423 | center |
| 12 | 1430 | east |
| 13 | 1642 | west |
| 14 | 1647 | center |
| 15 | 1651 | east |
| 16 | 1822 | west |
| 17 | 1828 | center |
| 18 | 1833 | east |
| 19 | 1900 | west |
| 20 | 1906 | center |

| | | | | |
|---|---|---|---|---|
| 21 | 1910 | east | | |

| Silver Bay Transect | | 6/1/95 | Salinity/Temperature Profile | Rutgers |
|---|---|---|---|---|
| Cast # | Time | Location | | |
| 0 | 1352 | Center | | |
| 1 | 1413 | Center | | |
| 2 | 1433 | Center | | |
| 3 | 1453 | Center | | |
| 4 | 1519 | Center | | |
| 5 | 1533 | Center | | |
| 6 | 1553 | Center | | |
| 7 | 1613 | Center | | |
| 8 | 1634 | Center | | |
| 9 | 1654 | Center | | |
| 10 | 1713 | Center | | |

### 7.3.4 Tidal Gage Data

| Location | Type | Parameter | Time Period | Source |
|---|---|---|---|---|
| Surf City | SIGMA 950 | Level | 5/9/95-6/29/95 | Rutgers |
| Surf City | SIGMA 950 | Level | 7/3/95-Present | Rutgers |
| Barnegat Inlet | | Level | Available | NOS |
| Loveladies | | Level | Available | USGS |
| Waretown | | Level | Available | USGS |
| Bay Shore | | Level | Available | USGS |
| Mantoloking | | Level | Available | USGS |

### 7.3.5 Meteorological Data

| Location | Parameters | Time Period | Source |
|---|---|---|---|
| Atlantic City | Wind Speed/Dir, Temp, etc. | Available | NWS |
| Oyster Creek GPU Nuclear | Wind Speed/Dir, Temp, etc. | Available | GPU |

### 7.3.6 River Flow Data

| Location | Parameter | Time Period | Source |
|---|---|---|---|
| Toms River | River Flow | Available | USGS |

### 7.4 June/July Data Set

#### 7.4.1 S-4 Data

| Location | SN | Parameter | Time Period | Source |
|---|---|---|---|---|
| Mantoloking | 237 | Vel/Dir/Sal/T | 1120 6/8/95 - 1800 6/8/95 | Rutgers |
| Surf City | 239 | Vel/Dir/Sal/T | 0840 6/8/95 - 1120 7/11/95 | Rutgers |
| Cedar Creek | 137 | Vel/Dir/Sal/T/Depth | 0910 6/22/95 - 0840 6/29/95 | Rutgers |
| Mantoloking | 237 | Vel/Dir/Sal/T | 0730 6/22/95 - 0830 7/11/95 | Rutgers |
| Barnegat Inlet | 238 | Vel/Dir/Sal/T | 1110 6/22/95 - 1030 7/11/95 | Rutgers |

#### 7.4.2 Marsh McBirney Data

| Location | Type | Parameter | Time Period | Source |
|---|---|---|---|---|
| Surf City | Bi-direction | Vel/Dir vs Depth | 0915-1720 6/8/95 | Rutgers |
| Mantoloking | Uni-direction | Vel/Dir vs Depth | 1123-1806 6/8/95 | Rutgers |
| Cedar Creek (Center) | Bi-direction | Vel/Dir vs Depth | 0913-1740 6/22/95 | Rutgers |
| Cedar Creek (West) | Uni-direction | Vel/Dir vs Depth | 0920-1720 6/22/95 | Rutgers |
| Cedar Creek (East) | Uni-direction | Vel/Dir vs Depth | 0910-1733 6/22/95 | Rutgers |
| Silver Bay | Bi-direction | Vel/Dir vs Depth | 0925-1620 6/29/95 | Rutgers |

#### 7.4.3 CTD Data

ADCP Transects 6/8/95 Salinity/Temperature Profiles Rutgers

| Cast# | Time | Location |
|---|---|---|
| 0501 | 8:30 | Marker #47 (Loveladies) |
| 0601 | 9:36 | Marker #47 |
| 0701 | 10:41 | Marker #47 |
| 0801 | 11:23 | Marker #42 |
| 0901 | 12:15 | Marker BI |
| 1001 | 13:35 | Marker#22 (Silver Bay) |
| 1101 | 14:07 | Marker #22 |
| 1201 | 14:30 | Marker #22 |
| 1301 | 14:50 | Toms River |
| 1401 | 15:16 | Toms River |
| 1501 | 15:27 | Marker #39 |
| 1601 | 15:37 | Marker #40 (Cedar Creek) |
| 1701 | 15:43 | Marker #40 |
| 1801 | 16:15 | Marker #40 |
| 1901 | 16:26 | Marker BB |
| 2001 | 16:40 | Marker #45/47 (Loveladies) |
| 2101 | 16:52 | Marker #45/47 |
| 2201 | 17:17 | Marker #45/47 |

### 7.4.4 Tidal Gage Data

| Location | Type | Parameter | Time Period | Source |
|---|---|---|---|---|
| Surf City | SIGMA 950 | Level | 5/9/95-6/29/95 | Rutgers |
| Surf City | SIGMA 950 | Level | 7/3/95-Present | Rutgers |
| Barnegat Inlet | | Level | Available | NOS |
| Loveladies | | Level | Available | USGS |
| Waretown | | Level | Available | USGS |
| Bay Shore | | Level | Available | USGS |
| Mantoloking | | Level | Available | USGS |

### 7.4.5 Meteorological Data

| Location | Parameters | Time Period | Source |
|---|---|---|---|
| Atlantic City | Wind Speed/Dir, Temp, etc. | Available | NWS |
| Oyster Creek GPU Nuclear | Wind Speed/Dir, Temp, etc. | Available | GPU |

### 7.4.6 ADCP Data

| Location | Parameter | Time Period | Source |
|---|---|---|---|
| Loveladies | Velocity Profile | 6/8/95 | Rutgers/USCOE |
| Toms River | Velocity Profile | 6/8/95 | Rutgers/USCOE |
| Cedar Creek | Velocity Profile | 6/8/95 | Rutgers/USCOE |
| Silver Bay | Velocity Profile | 6/8/95 | Rutgers/USCOE |
| Barnegat Inlet | Velocity Profile | Available | USCOE |

### 7.4.7 River Flow Data

| Location | Parameter | Time Period | Source |
|---|---|---|---|
| Toms River | River Flow | Available | USGS |

## 7.5. Comments on Applications of Field Data for Numerical Modeling

The use of field data in numerical modeling requires substantial processing and evaluation before the data sets are accepted and incorporated into the modeling procedure. All data must be screened for completeness and reasonableness. Gaps must be identified, random noise must be removed by filtering.

The data obtained for this project are extensive and comprehensive, but a few data gaps do exist for the following reasons:

A. Equipment Malfunction. Some equipment either did not work as it was intended or the instrument itself failed.

B. Lost/Damaged Equipment. Barnegat Bay is an extremely dynamic environment. Equipment can frequently be either lost, stolen, or damaged.

C. Availability of Equipment. In some cases although it was desirable to obtain certain data in a certain location at a certain time, there was not enough equipment to go around, either due to availability or cost. The best data were collected with the best available equipment.

D. Weather. To deploy some equipment properly, favorable weather is required.

Although the project called for two data sets to be acquired, one in winter and one in summer, a third set was collected in the spring period because of the availability of the equipment. Thus, an extra data set was produced within the scope of this project. The third set of data proved to be very valuable and contributes substantially to collection of field data available to drive, calibrate, and verify a two-dimensional depth-averaged circulation model.

## 8.0 Preliminary Analysis of Circulation Pattern

### 8.1. Tidal Exchange Rate

As defined in Section 4.2.3., the tidal exchange rate (R) is the ratio between the volume of new ocean water ($V_0$) and the total volume ($V_F$) of water entering the bay on the flood tide. The most important determinant is the longshore current. The longshore current deflects the ebb flow downcoast and delivers the supply of new ocean water for the flood. Without a longshore current all of the exchange would be by a relatively inefficient local mixing processes in the coastal zone. Usually it is not possible to predict the tidal exchange ratio from theory. However, it can be calculated by using the known temporal variation of salinity by using the following formula (Fischer et al., 1979):

$$R=\frac{S_F-S_E}{S_0-S_E}$$

where

$S_F$ = the average salinity of water entering the bay on the flood tide,
$S_E$ = the average salinity of water leaving the bay on the ebb tide,
$S_0$ = the salinity of ocean water.

Accurate determination of average flood and ebb salinities requires complete cross-sectional measurements of both salinity and velocity throughout the tidal cycle. In this study, as part of the field data collection network, an S-4 was installed at the inlet, which provides the temporal variation of salinity at one location.

As a first approximation, the tidal exchange rate is calculated by the following approximate formula using salinity at one point:

$$R=\frac{S_{fmax}-S_{emin}}{S_0-S_{emin}}$$

where $S_0$ is the ocean salinity, $S_{fmax}$ is the maximum salinity on the flood tide, and $S_{emin}$ is the is the minimum value on the ebb tide. The above approximation formula is expected to yield a reasonable product because the flow velocity and salinity are quite uniform at the inlet, and the tidal range is not very large compared with the mean water depth. The time variation of the tidal exchange rate is shown in Fig. 8-1. During the time period, June 22 to July 11, 1995, the average tidal exchange rate is 0.37; i.e., thirty-seven percent of the water entering the bay on the flood tide was new ocean water, or, in other words, sixty-three percent of the flood tide water is composed of Bay water that exited on the previous ebb tide. The significance of this calculation is that it is only the 37% of the flood volume that is available for dilution of any substance in the bay and it lengthens the time for complete exchange of the Barnegat Bay volume by tidal action. The variation of tidal exchange rate through time (tidal cycle) (Fig.8-1) is caused by

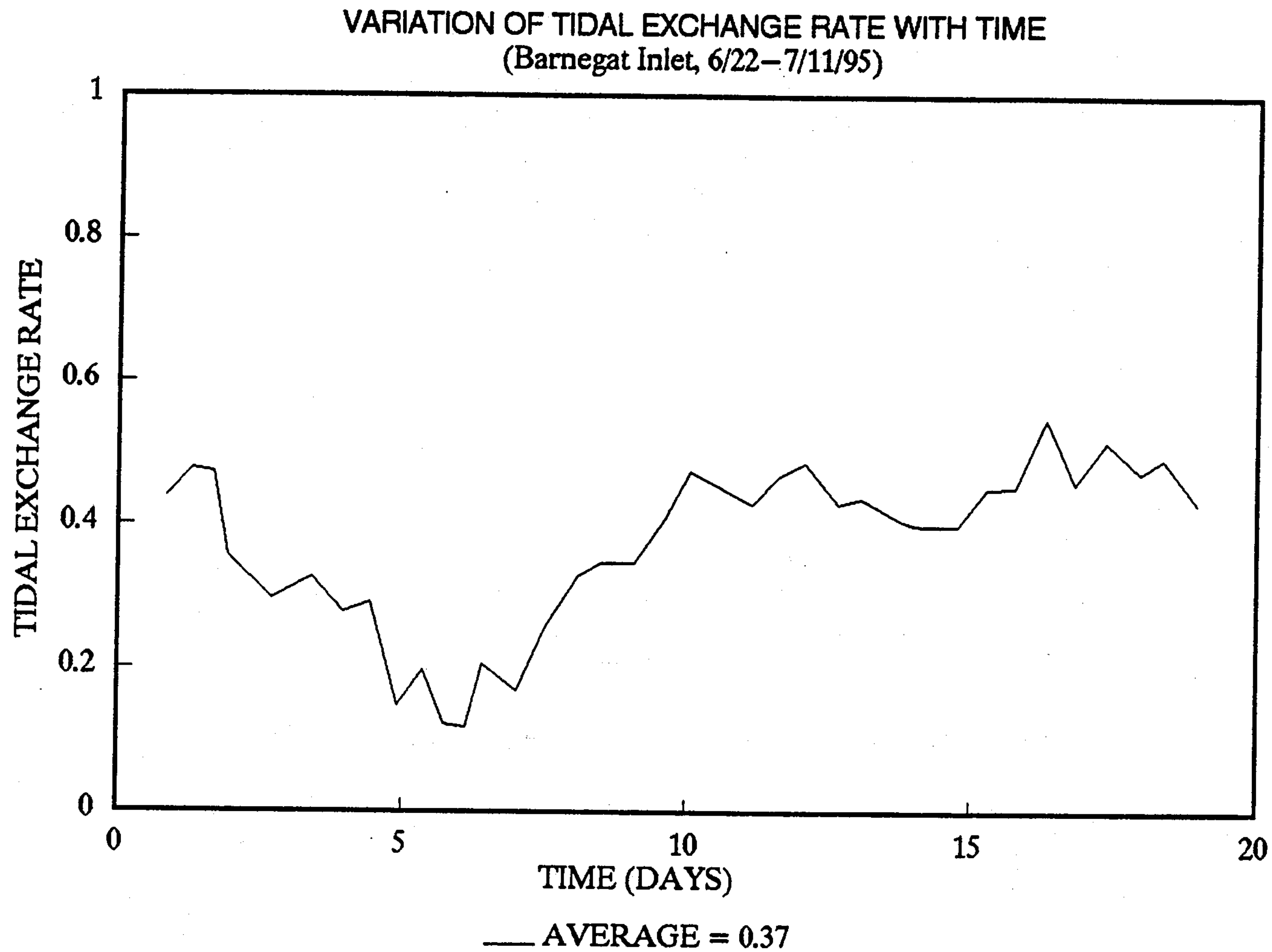



Figure 8-1. Variation of tidal exchange rate with time at Barnegat Inlet, 6/22/95-7/11/95.

change in tidal range, variation of fresh water inflow, and the wind. The tidal exchange rate is an important value in the pollutant concentration calculation, as demonstrated in Section 4.2.3.

## 8.2. Tidal Flushing Time

### 8.2.1. Tidal flushing time based on the classical tidal prism model

The volume of water in Barnegat Bay was estimated to be 238,000,000 $m^3$ (1974 data). The tidal prism was measured to be 11,200,000 $m^3$ (1980 data). Based on the classical tidal prism theory, neglecting the surface and ground freshwater inflows and precipitation/evaporation, complete turnover of Barnegat Bay takes place every 21 tidal cycles, or approximately 11 days.

Asheley's (1987) measured tidal prism was 12,400,000 $m^3$ in 1987, which shows a stable condition since 1980. However, tidal prism has changed since the completion of jetty modification at Barnegat Inlet in June, 1991. The U.S. Army Corps of Engineers has measured the tidal prism for the last three years after the jetty modification. When these new values become available, the flushing time should be recalculated.

It should also be pointed out that if the classical tidal prism model, which is equivalent to the single well-mixed cell model, is applied to back-calculate the groundwater fresh water input, the groundwater input will be substantially larger than that estimated by U.S.G.S. During the back-calculation, the solution for salinity in Section 4.2.2 (Tidal Prism Model) is used. It can be seen in the solution that with shorter flushing times, larger quantities of fresh groundwater input will be required to produce bay salinity, assuming all other variables remain constant. It is apparent that by using the classical tidal prism model, the flushing time is under-estimated. This is due to the invalid assumption that the bay volume is completely mixed and exchanged in the classical tidal prism model.

### 8.2.2. Tidal flushing time based on the two mixed-cell model

Moser et al. (1995) used a two-cell mass balance model to calculate flushing time. They used two approaches. One approach is the same as the Classical Tidal Prism model (including surface and ground freshwater inflows, and precipitation/evaporation), but using two cells. Using this approach the flushing time was calculated as 15 days, roughly twice that obtained by using a single cell (7 days). During the calculation groundwater input was estimated using average salinity in the Bay, as described in Sec. 4.2.1 and 4.2.2 for single cell and Sec. 4.3.1 for two cells. Using the two-cell model, the amount of fresh groundwater required to satisfy the measured salinity values was still much larger than the quantities estimated by the USGS (1995). The second approach, also using two cells, proceeded from the amount of fresh groundwater estimated by the USGS to back-calculate the flushing time. The resulting values for flushing time were very different (44 days versus 15 days). The later figure is much closer to the preliminary estimate produced in this report using the tidal exchange model, which is described in the following section.

8.2.3. Tidal flushing time based on the calculated tidal exchange rate

In the single cell classical tidal prism model, if only the new ocean water, instead of the total volume of water, entering the bay on the flood tide is used, the tidal flushing time is calculated to be 58 days, or approximately 112 tidal cycles. This is approximately equal to that (96 tidal cycles) mentioned by Chizmadia et al (1984). They cite Carpenter (1966) as the source for this flushing time.

Using the flushing time estimated from the tidal exchange model, the amount of fresh groundwater direct input to the bay required to dilute the ocean water is minimal; this is in agreement with U.S.G.S.'s estimate. This calculation is important because it means that nearly all of the inputs to the bay from the land side enter through the surface streams. Thus, if the water quantity and quality of the surface streams can be determined, it will be much easier to apply the models and approach the understanding of bay hydrodynamics. Likewise, it will assist in the identification of substances entering from the ocean through the inlet.

## 8.3. Horizontal Distribution of Salinity and Temperature

The horizontal distributions of salinity and temperature are shown in Figs. 8-2 to 8-9. S-4 salinity and temperature are the long-term (about a month) averaged values at one location in the vertical direction. CTD salinity and temperature are the short-term (from several minutes to a tidal cycle) averaged values of multiple locations in the vertical direction.

The horizontal salinity distribution follows the expected trend that salinity is the highest at Barnegat Inlet, and decreases in the north and the south directions. An unusually high salinity was found at the north bank of the Toms River (Fig. 8-5); this might be due to local trapping of salt water.

The horizontal temperature distribution is more complex because the temperature is not only dependent on temperature of freshwater inflows and ocean water, but also heat transfer across the water-air interface. The heat transfer across the interface is particularly important in Barnegat Bay because of its shallowness. It can be observed from the S-4 data that temperature varies semi-diurnally at Barnegat Inlet showing strong tidal (ocean) influence, whereas within the bay temperature varies diurnally showing strong local heat transfer. It is observed that in the cold season temperature varies widely within the Bay, whereas in the summer temperature is almost uniform.

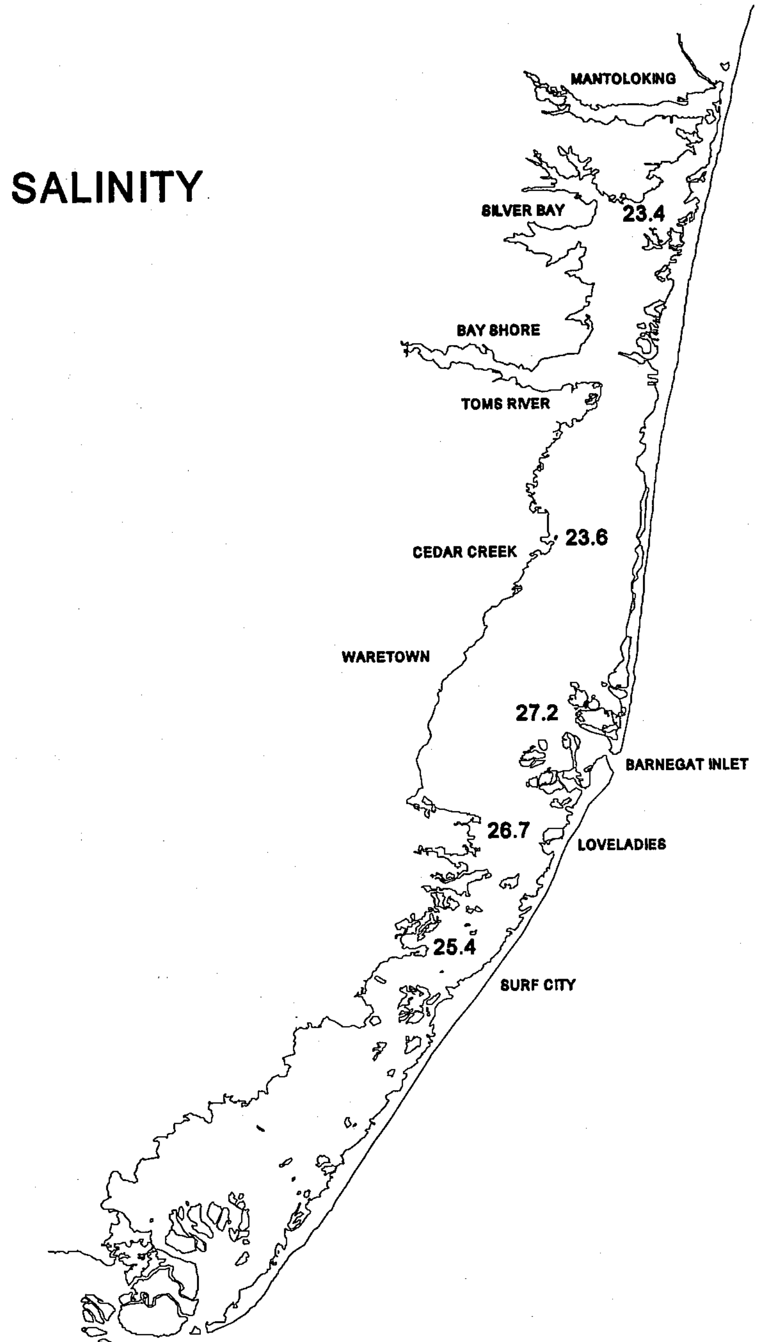



Figure 8-2. Average salinity obtained by the S-4 in January 1995

# SALINITY

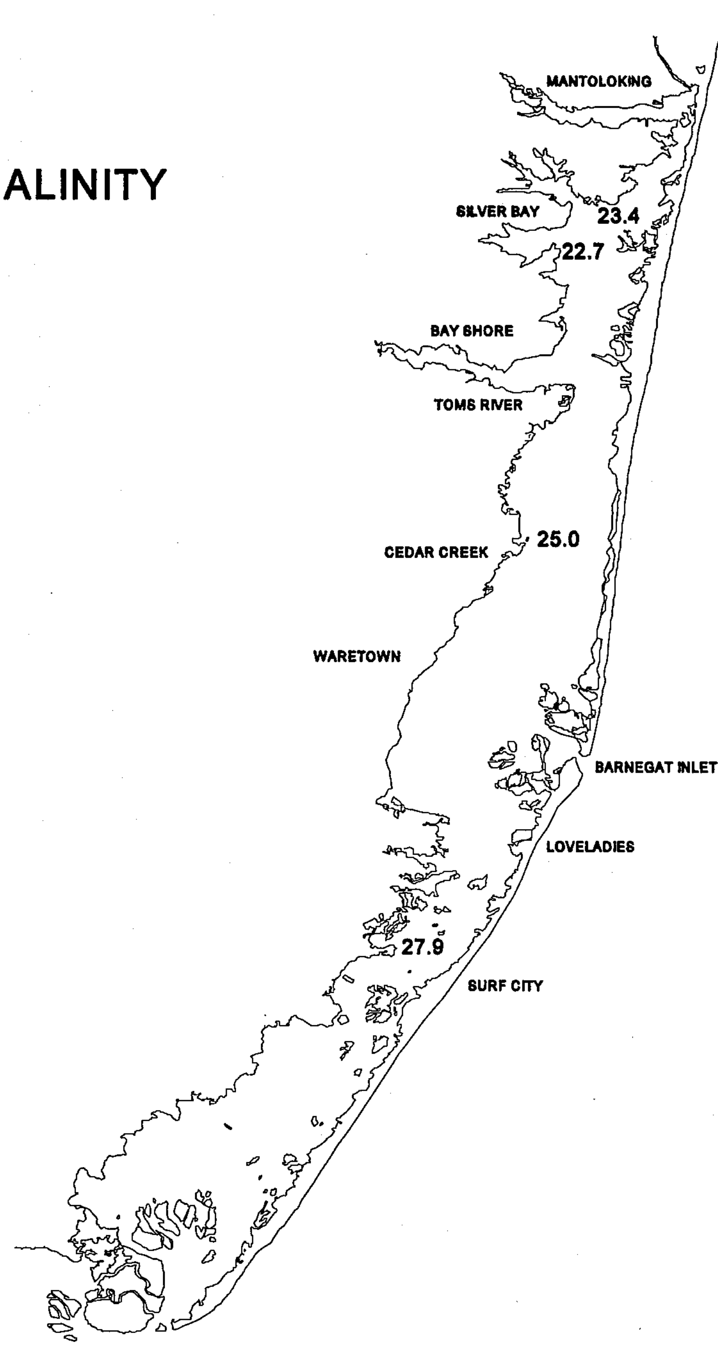



**Figure 8-3. Average salinity obtained by the S-4 in May 1995**

# SALINITY

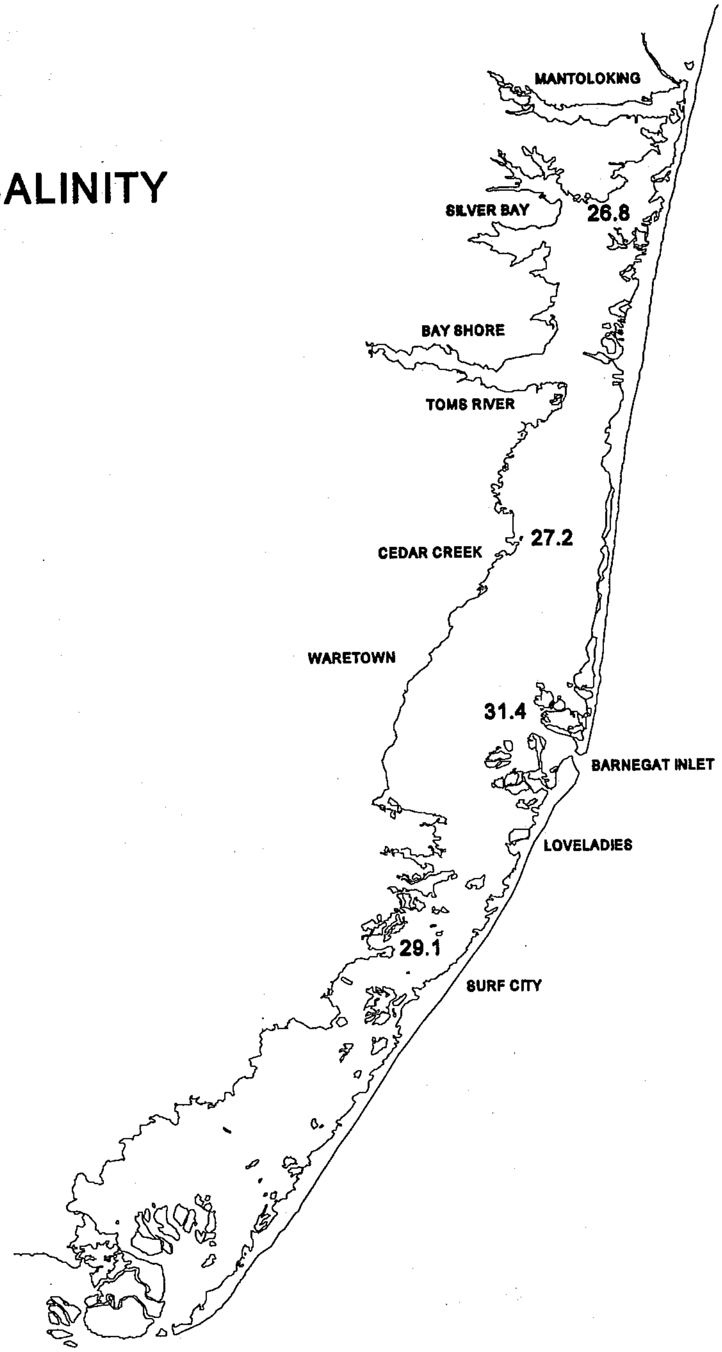



**Figure 8-4. Average salinity obtained by the S-4 in June/July 1995**

# CTD SALINITY

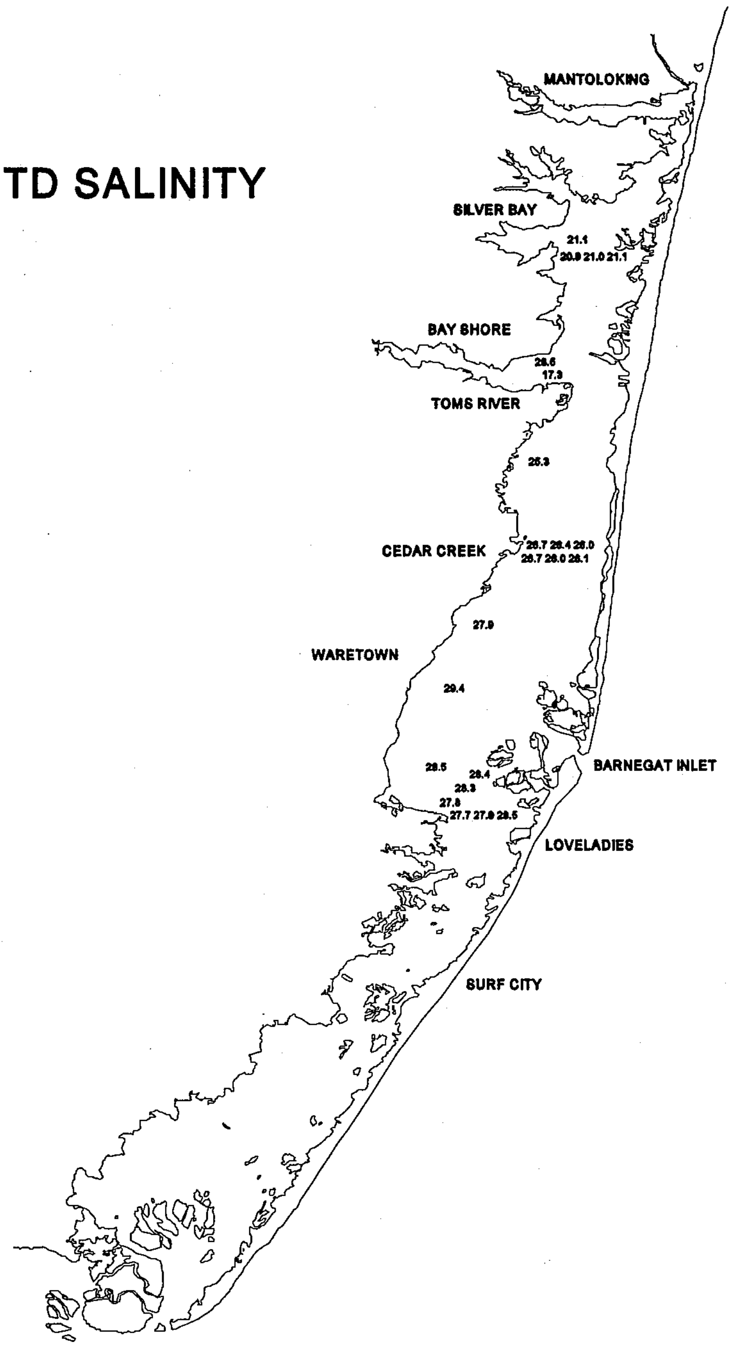



**Figure 8-5. Average salinity obtained by the CTD in May/June 1995**

# TEMPERATURE

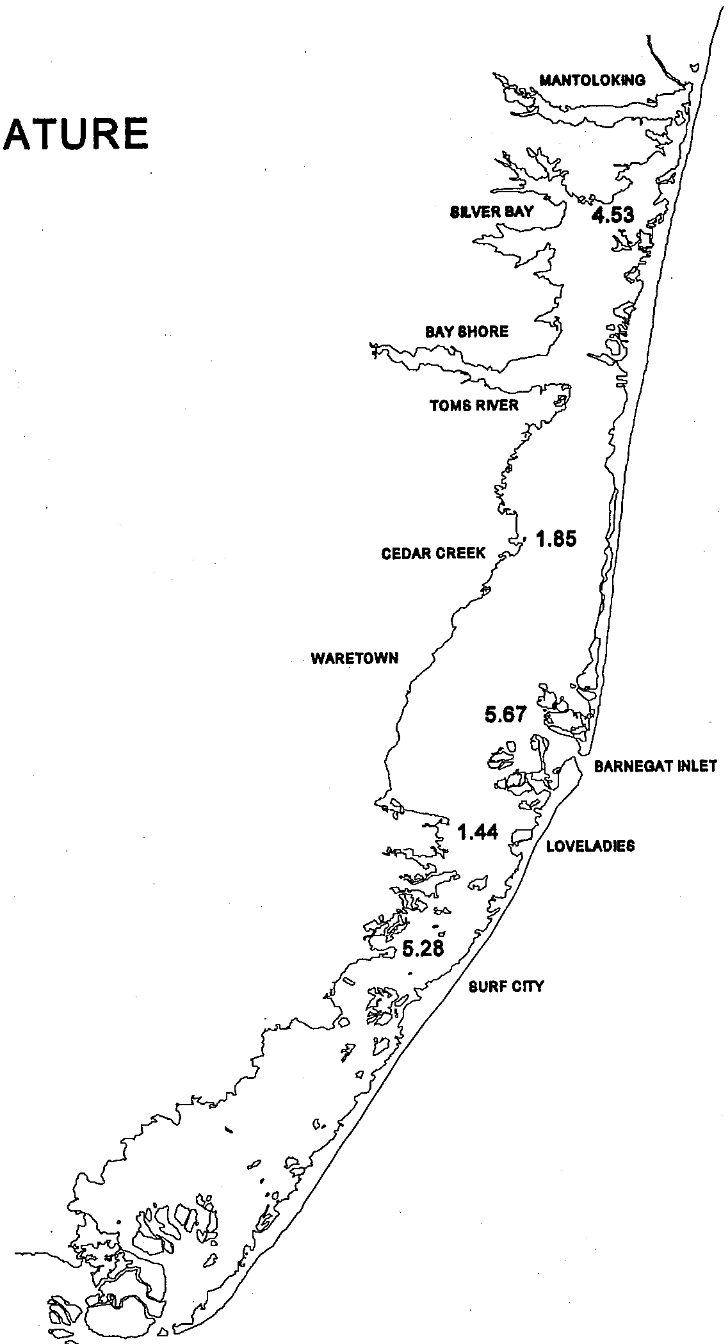



Figure 8-6. Average temperature obtained by S-4 in January 1995

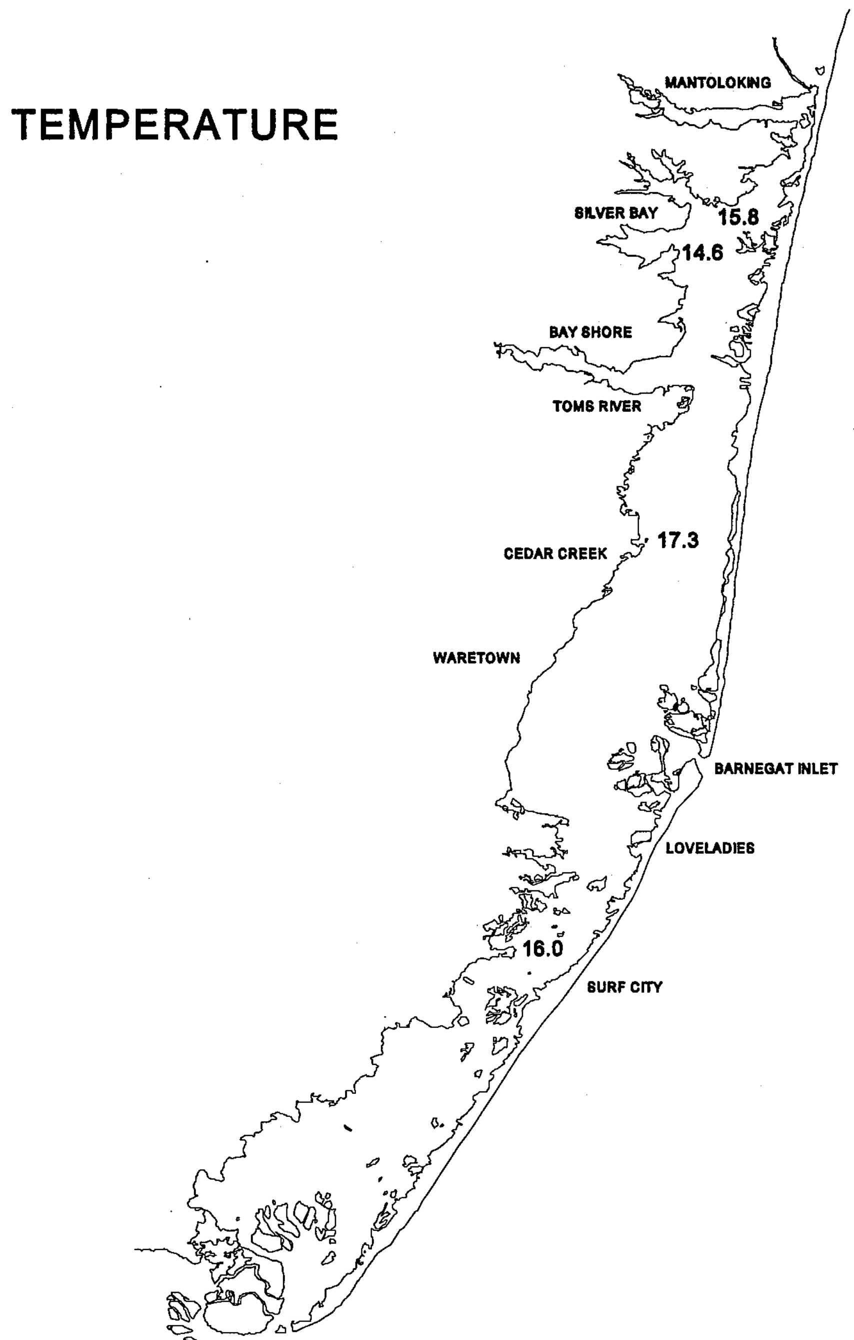



**Figure 8-7. Average temperature obtained by S-4 in May/June 1995**

# TEMPERATURE

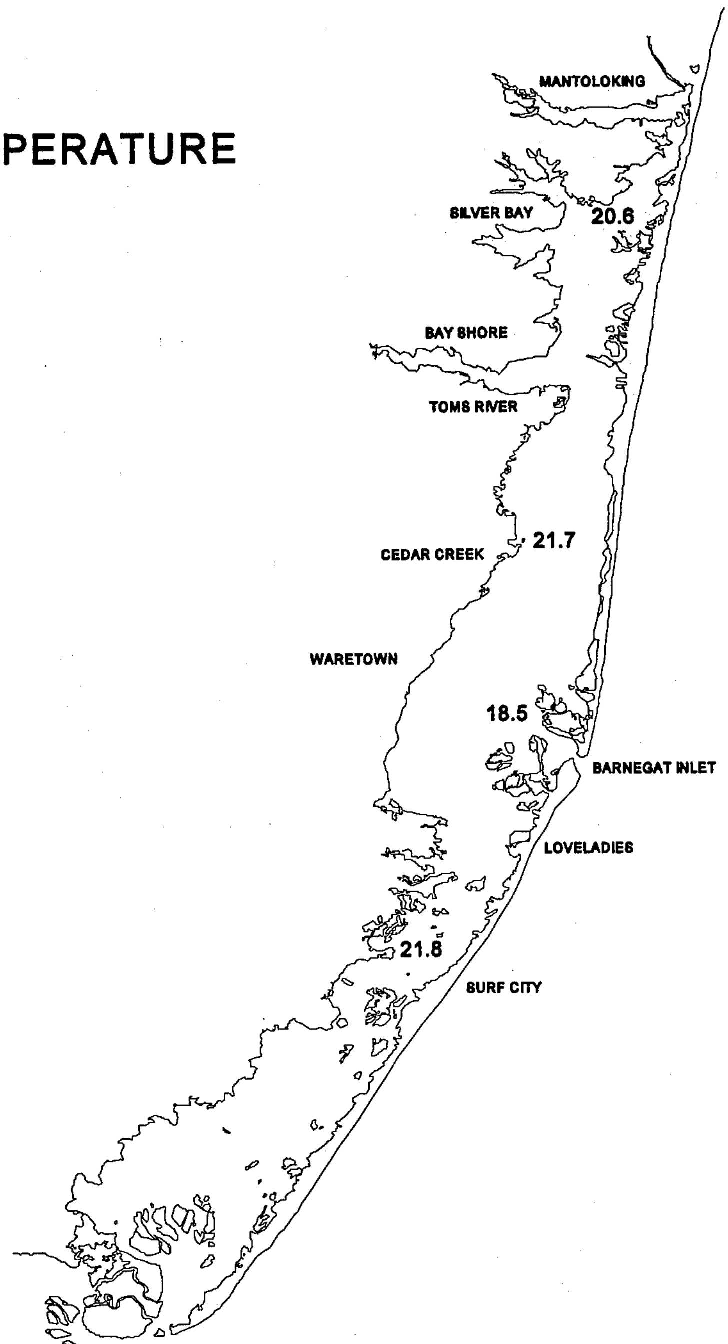



**Figure 8-8. Average temperature obtained by the S-4 in June/July, 1995**

CTD
TEMPERATURE
(deg C)

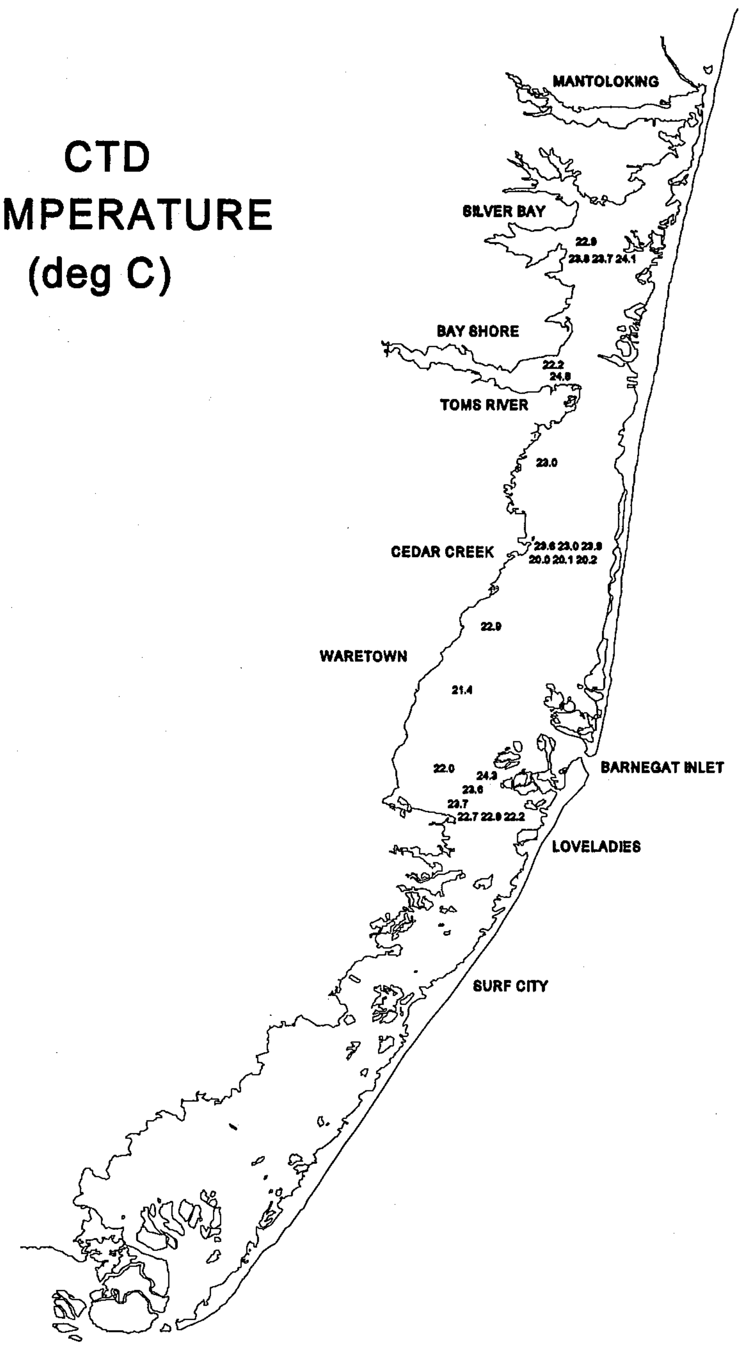



Figure 8-9. Average temperature obtained by the CTD in May/June 1995

## 8.4. Vertical Distribution of Salinity and Temperature

Vertical distributions of salinity and temperature were measured and collected by CTD casts. A typical vertical distribution of salinity and temperature in the middle portion of the bay outside Cedar Creek is shown in Figs. 8-10 and 8-11. During flood tide (Fig. 8-10), there is a slight salinity and thermal stratification, however during the ebb tide (Fig. 8-11) it becomes uniform. A typically vertical distribution of salinity and temperature in the northern portion of the bay outside Silver Bay is shown in Figures 8-12 and 8-13. Independent of flood or ebb tide effects, salinity and temperature are uniform. From these typical profiles, and others presented in the Appendix, it is concluded that Barnegat Bay is a fully-mixed bay in the vertical direction, except in some local areas.

## 8.5. Time Series Analysis of S-4 Current Velocity Data

### 8.5.1. Separation of tidal current

Based on the hypothesis of linear coupling of each tidal current constituent and non-tidal current constituent, the observed current can be expressed as follows

$$u_i(t)=P_{i0}+A_{i0}+\sum^M [A_{ik}\cos(\omega_{kt})+B_{ik}\sin(\omega_{kt})],\ i=1,2$$

where $P_{i0}$ is the perturbation compared to the tidal current, $A_{i0}$ is the mean current, $A_{ik}$ and $B_{ik}$ are constant coefficients representing tidal signals, t is the time, and $\omega_k$ are known frequencies for tidal constituents. The subscript "I" denotes north or south component and M is the number of the tidal constituents to be analyzed. In this research M=6 was chosen, which corresponds to $M_2$, $S_2$, $N_2$, $O_1$, $K_1$ and $M_4$, the dominant tidal current constituents in Barnegat Bay. $M_2$, $S_2$, and $N_2$ are approximately semi-diurnal periods, $O_1$ and $K_1$ are approximately diurnal periods, and $M_4$ is approximately 3 hours resulting from nonlinear interaction in shallow waters. By applying the least square harmonic techniques, $A_{i0}$, $A_{ik}$, and $B_{ik}$ can be found, then the detide current can be calculated by subtracting the tidal signals, that is

$$u_{dti}(t)=P_{i0}+A_{i0}=u_i(t)-u_{ti}(t),\ i=1,2$$

$$u_{ti}(t)=\sum^M [A_{ik}\cos(\omega_{kt})+B_{ik}\sin(\omega_{kt})],\ i=1,2$$

where $u_{dti}$ is the detide current and $u_{ti}$ is the tidal current.

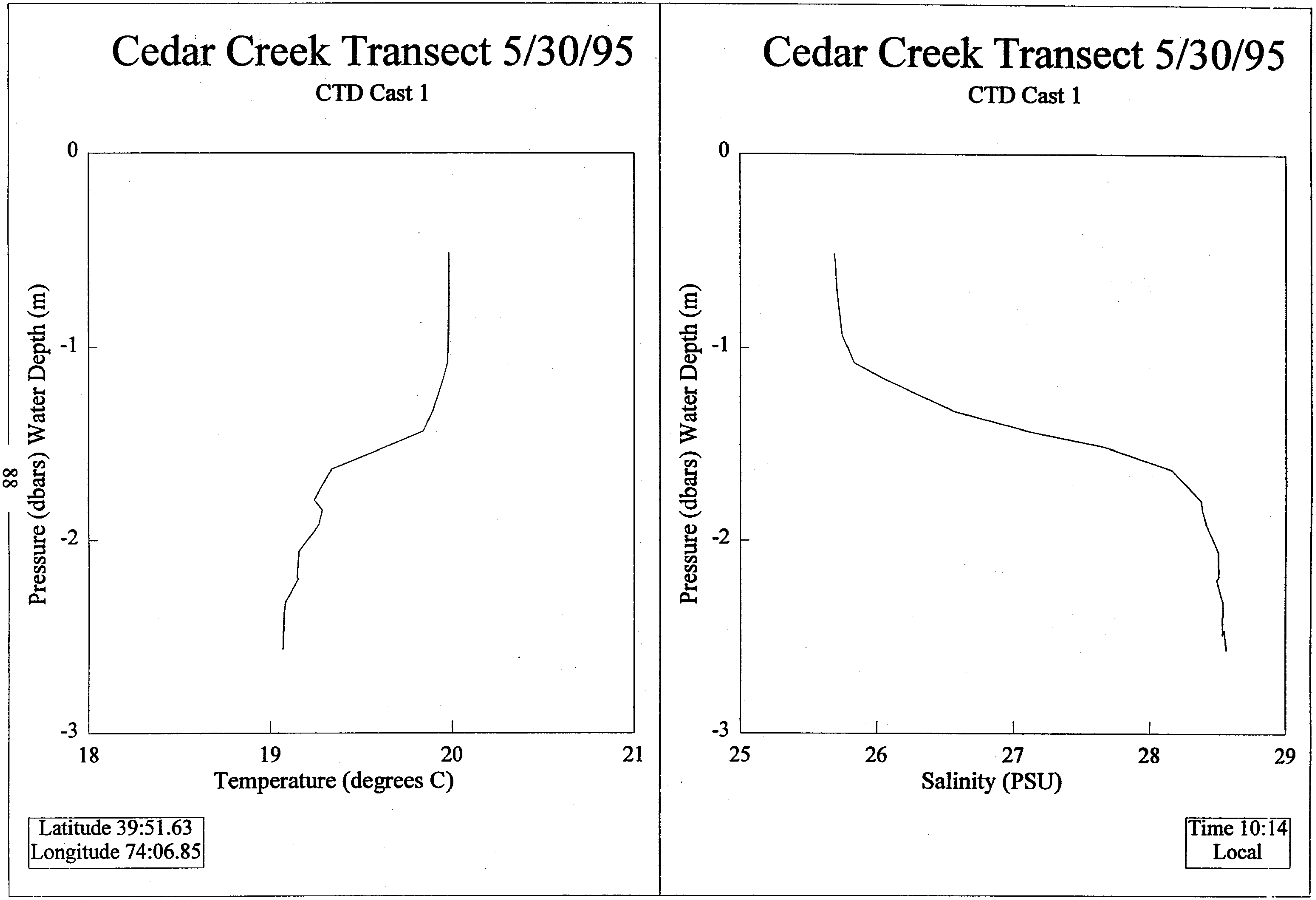



Figure 8-10. Vertical distribution of temperature and salinity at Cedar Creek during flood tide

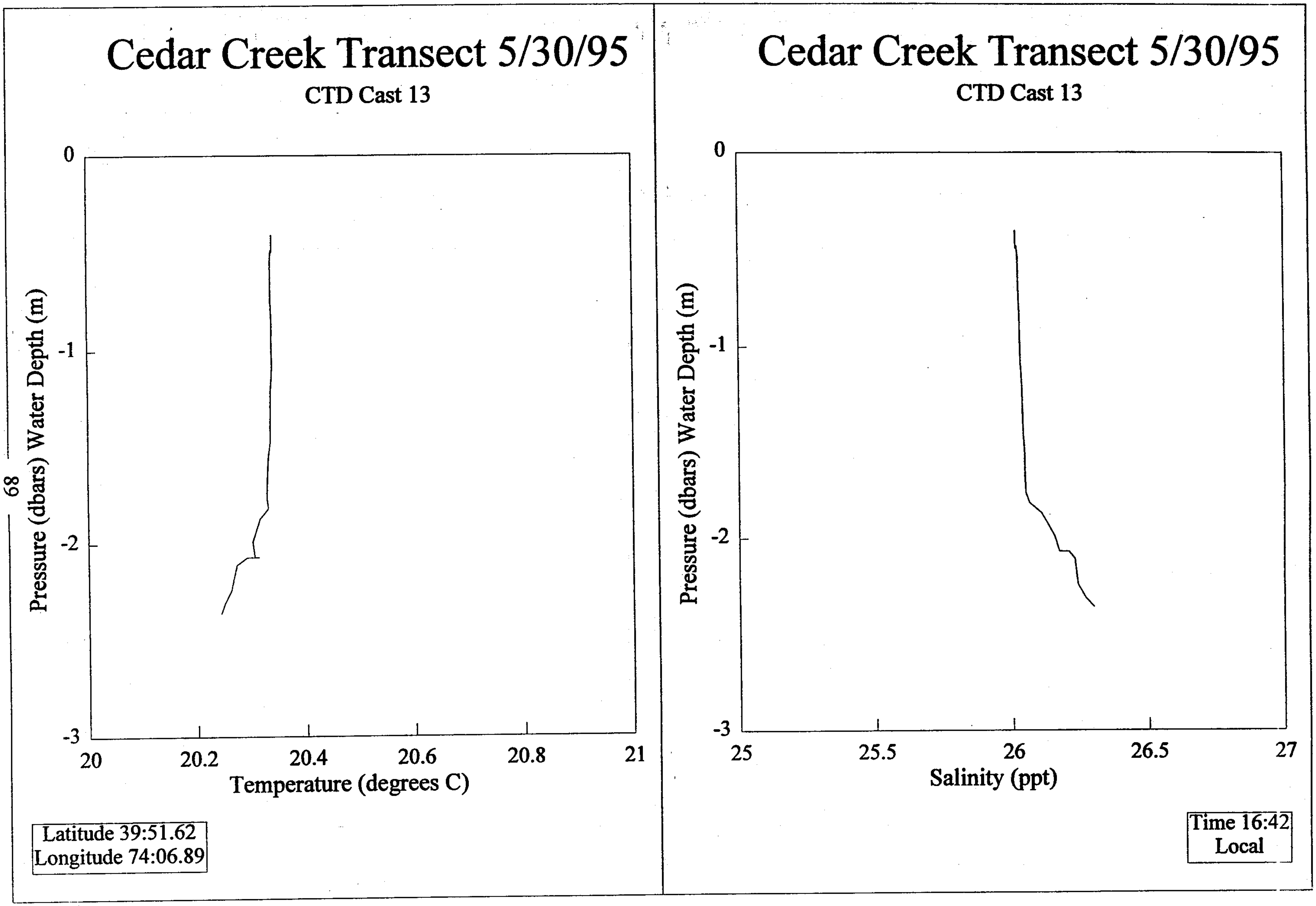



Figure 8-11. Vertical distribution of temperature and salinity at Cedar Creek during ebb tide

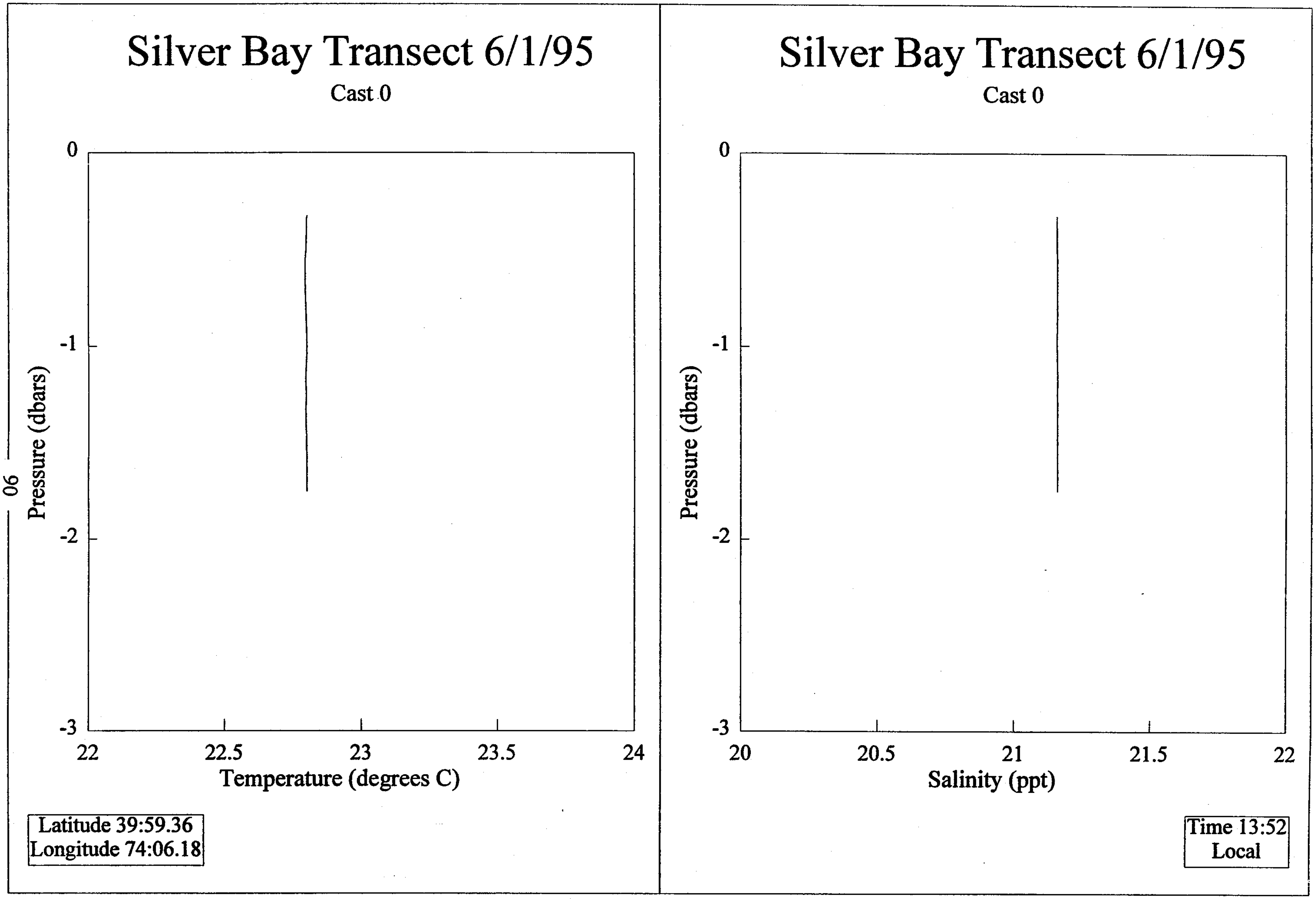



Figure 8-12. Vertical distribution of temperature and salinity at Silver Bay during flood tide

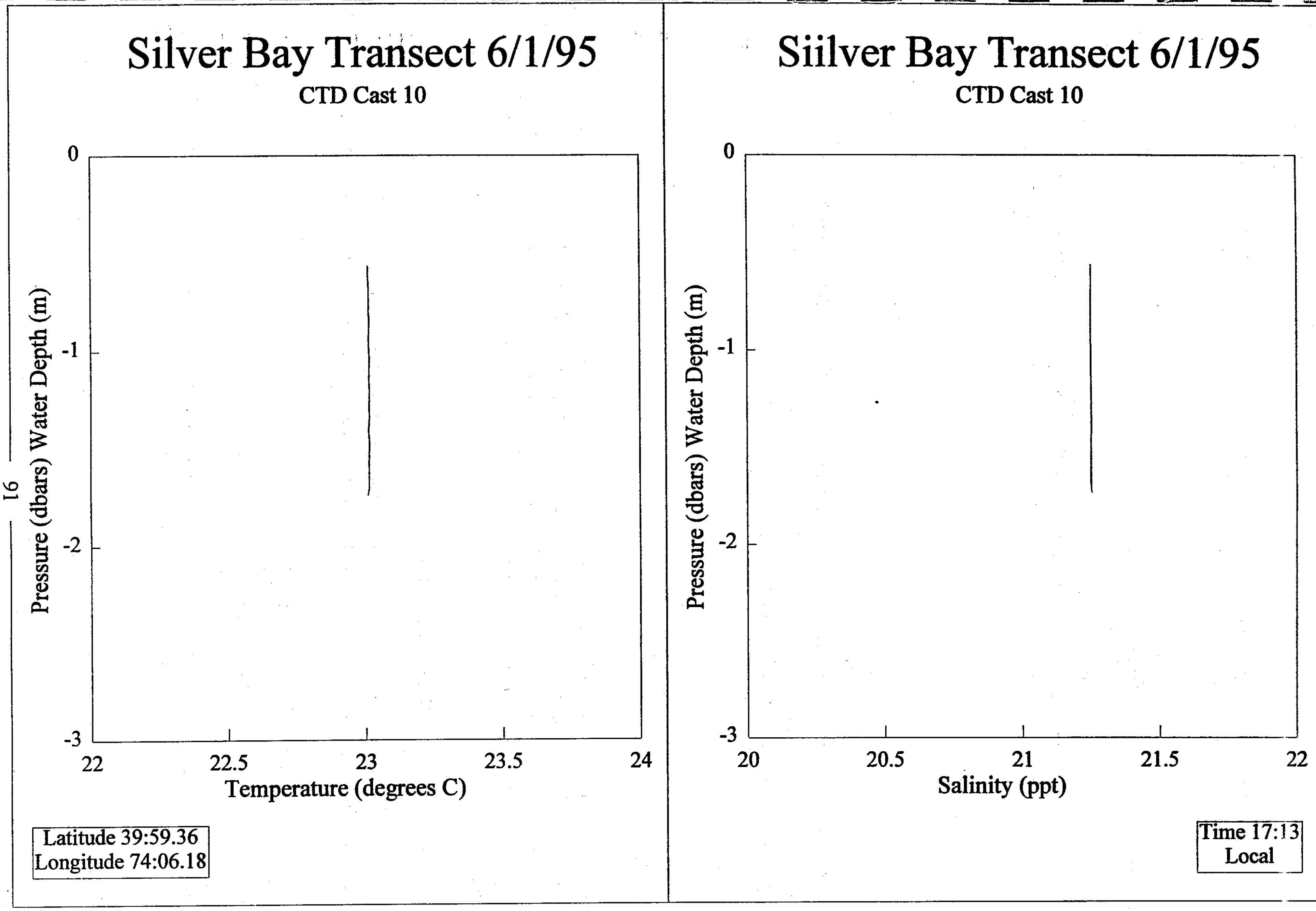



Figure 8-13. Vertical distribution of temperature and salinity at Silver Bay during ebb tide

In order to remove tidal signals further and other high frequency signals, the 30 hour low-pass filter was used to pass the detide current and obtain the filtered current.

### 8.5.2. Wind-Induced Current and Background Current

Suppose that the background current is relatively stable (physically it is the current when wind stress goes to zero) and the wind-induced current varies linearly with the wind speed, we can further split the filtered current into three constituents:

$$u_{dtf}=u_b+u_w+u_p$$

$$v_{dtf}=v_b+v_w+v_p$$

where ($u_{tdf}$, $v_{dtf}$) represents the north and east components of the filtered detide currents, ($u_b$,$v_b$) is the background current, ($u_w$, $v_w$) is the wind-induced current, ($u_p$,$v_p$) is the current perturbation which may be caused by other forcing terms or instrument error, and

$$u_w=aW_x+bW_y$$

$$v_w=cW_x+dW_y$$

where (Wx,Wy) represent north and east components of wind speed. By means of standard linear regression (the least squares technique), background current ($u_b$, $v_b$) and wind drift factors (a,b,c,d) can be calculated for a pair of wind and current data sets. We chose the time period during which both the current and wind data were available. Thus, the wind-induced current was deduced.

### 8.5.3. Cross-correlation between wind and measured current

The standard correlation analysis method was applied to the components of the filtered current and wind. The correlation coefficients were calculated from the following formula:

$$R_{XY}(\delta t)=\frac{\sum[(X_i(t+\delta t)-X_m)(Y_i(t)-Y_m)]}{\sum[X_mY_m]}$$

where X and Y are two series (wind and current) of record, $\delta t$ the time lag between the two series, and $X_m$ and $Y_m$ are the mean values of the X and Y series.

### 8.5.4. Major findings of the time series analysis of S-4 current data

Results of the time series analysis of S-4 current data at two locations are shown in Figs. 8-14 to 8-19.

a. A west wind is causing a two-layer current structure for the entire area of the Bay with surface current moving to the east and bottom current to the west. This is particularly obvious at Loveladies where the cross-correlation coefficient is 0.88 when the time lag is approximately zero (see Fig. 8-19).

b. A south wind is causing a two-layer structure in the northern portion of the Bay with surface current moving toward the north and the bottom current toward the south. This is particularly obvious at the location outside Silver Bay where the cross-correlation coefficient is 0.70 when the time lag is 12 hours (Fig. 8-16). This wind-induced two-layer current structure is combined with the tidal current in the same north-south orientation, thus it is not easily detectable. The time-series analysis is a useful means for the detection.

c. The magnitude of wind-induced current is on the order of the tidal current in the northern portion of the Bay outside Silver Bay (Figs. 8-14 and 8-15).

d. The magnitude of wind-induced current in the southern portion of the Bay outside Loveladies is much smaller than the tidal current, approximately one-sixth (Figs. 8-17 and 8-18).

Silver Bay (May)

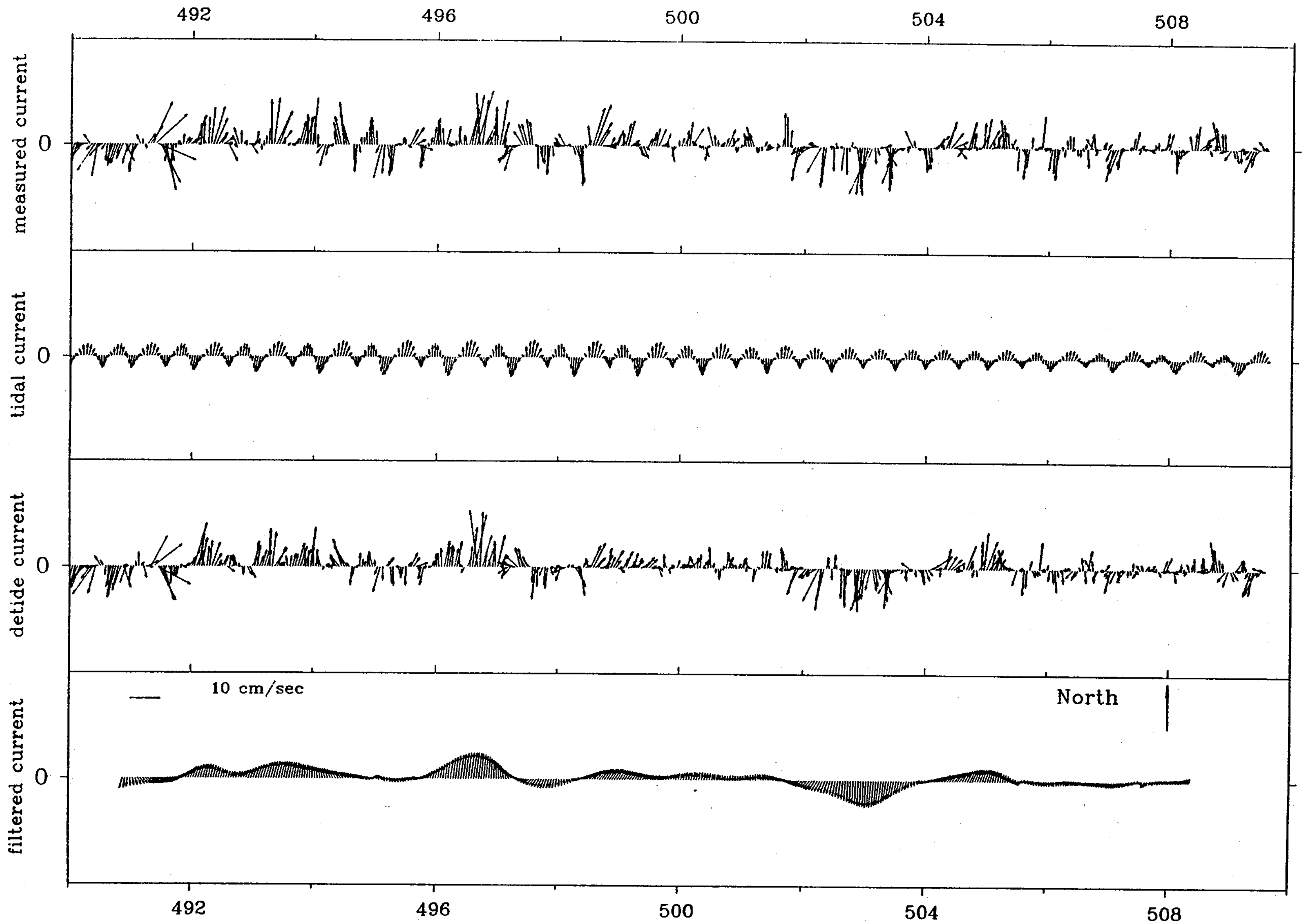



Figure 8-14. Results of time series analysis of current data from S-4 instrument at Silver Bay, May 1995.

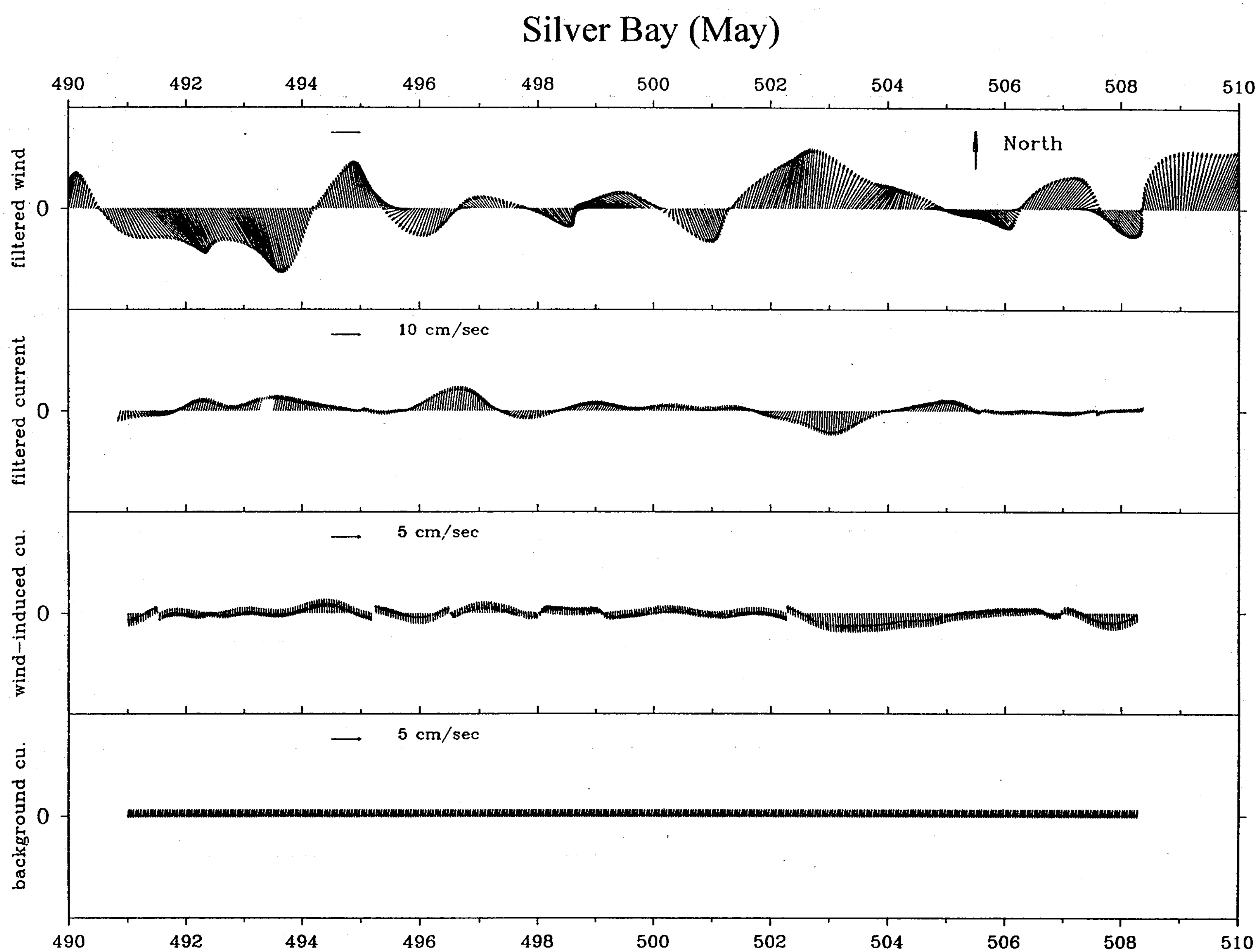



Figure 8-15. Results of time series analysis of current and wind data at Silver Bay, May 1995.

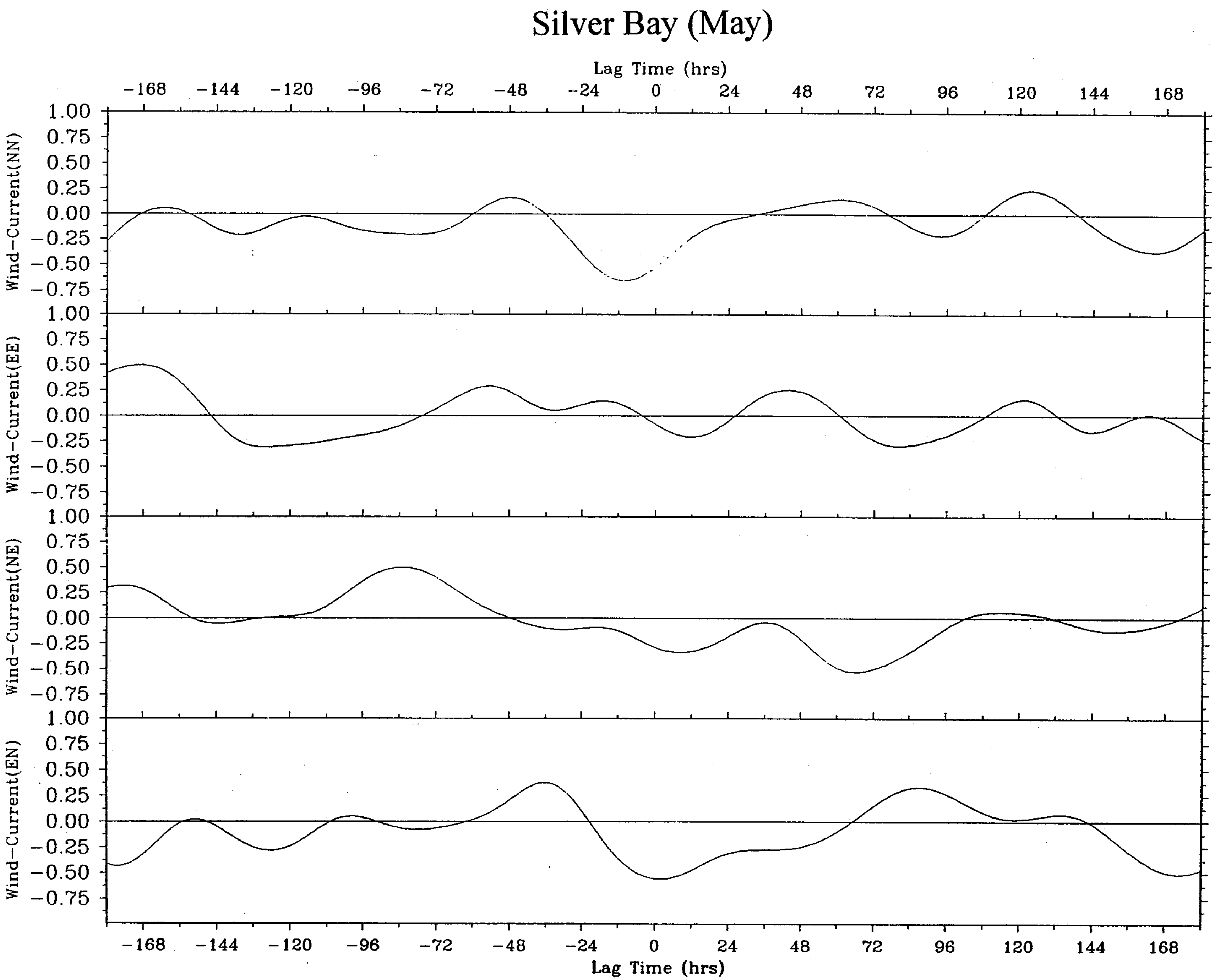



Figure 8-16. Cross-correlation between wind and current at Silver Bay, May 1995.

# Loveladies (January)

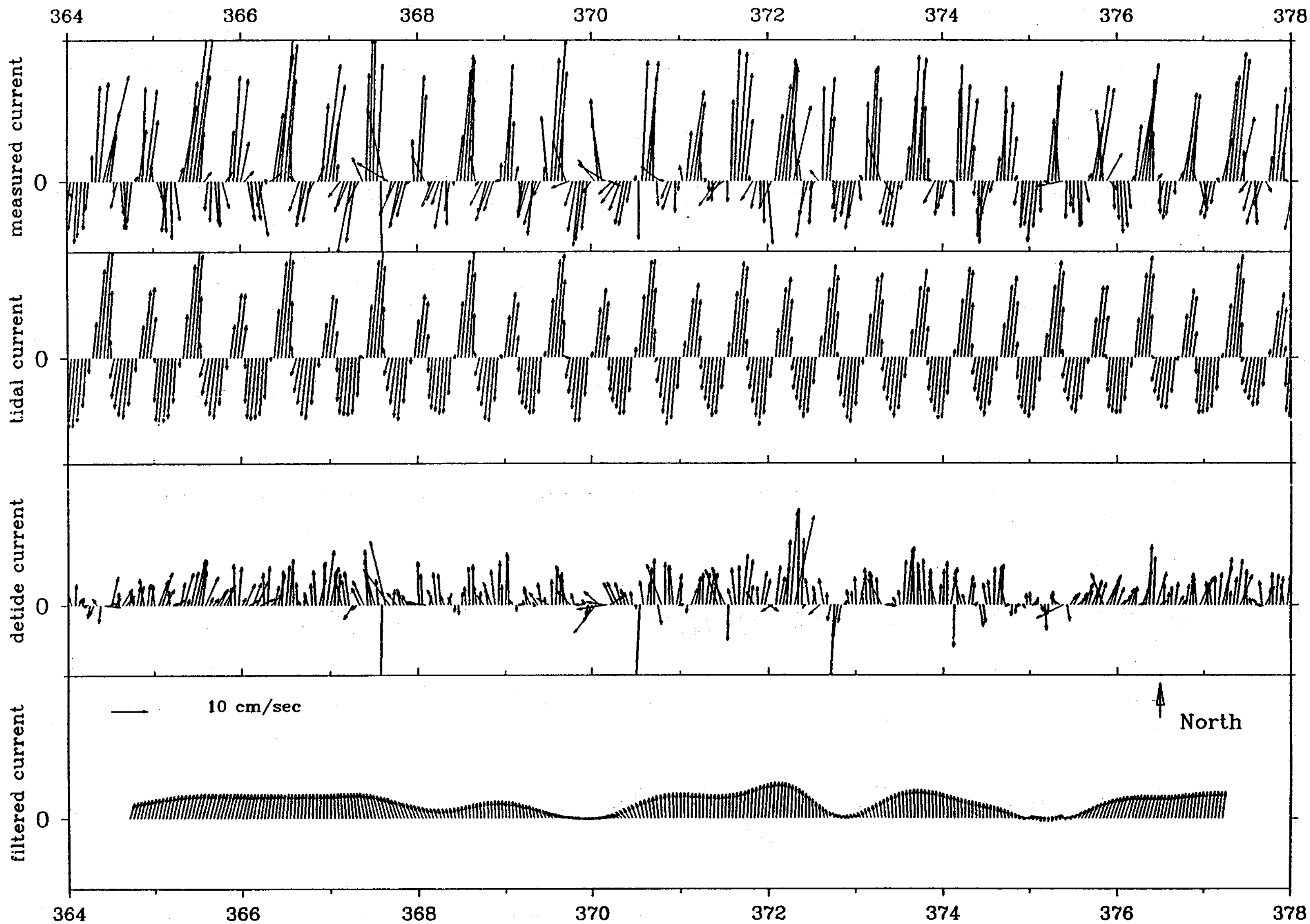



Figure 8-17. Results of time series analysis of current data from S-4 instrument at Loveladies, January 1995.

## Loveladies (January)

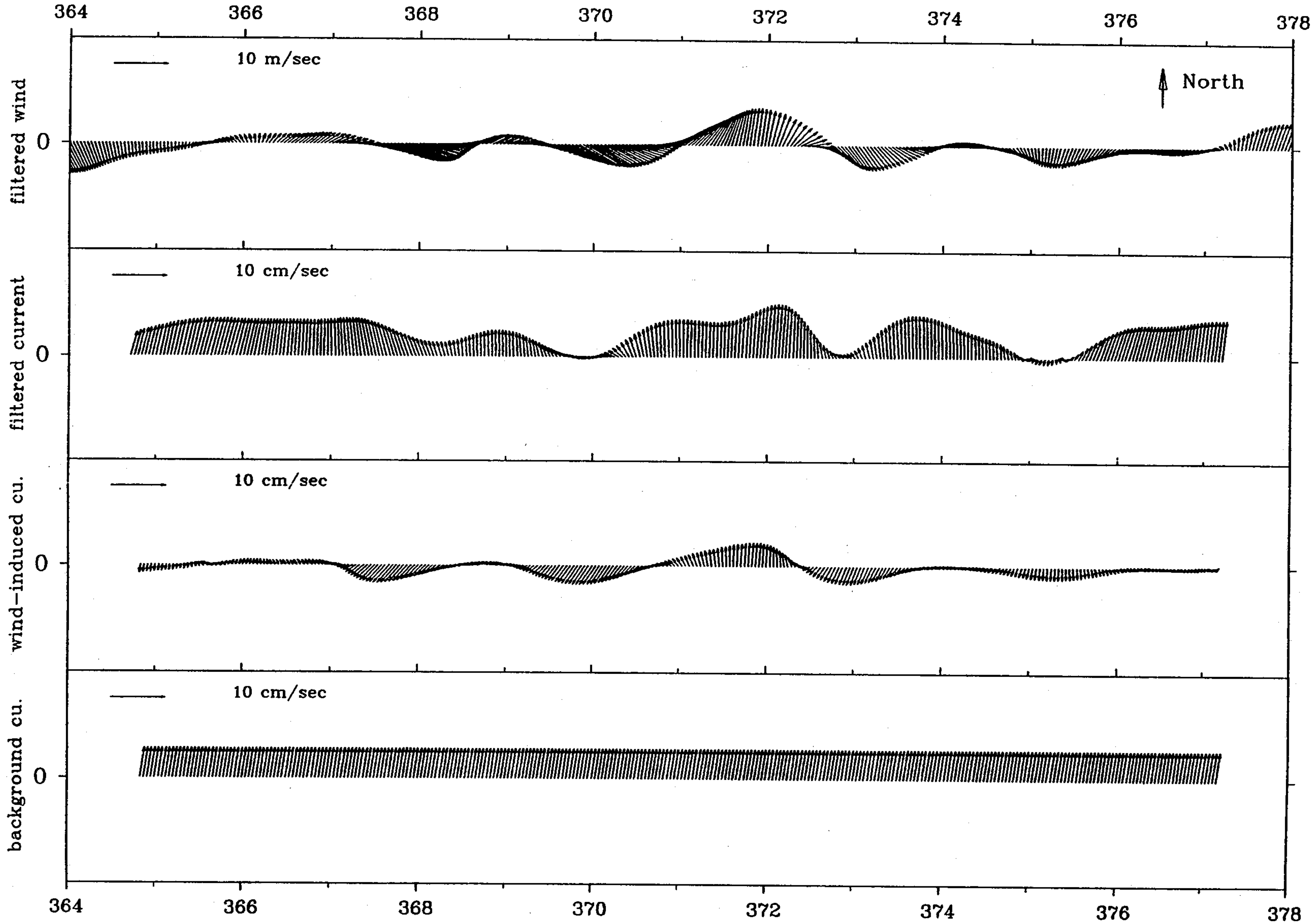



Figure 8-18. Results of time series analysis of current and wind data at Loveladies, January 1995.

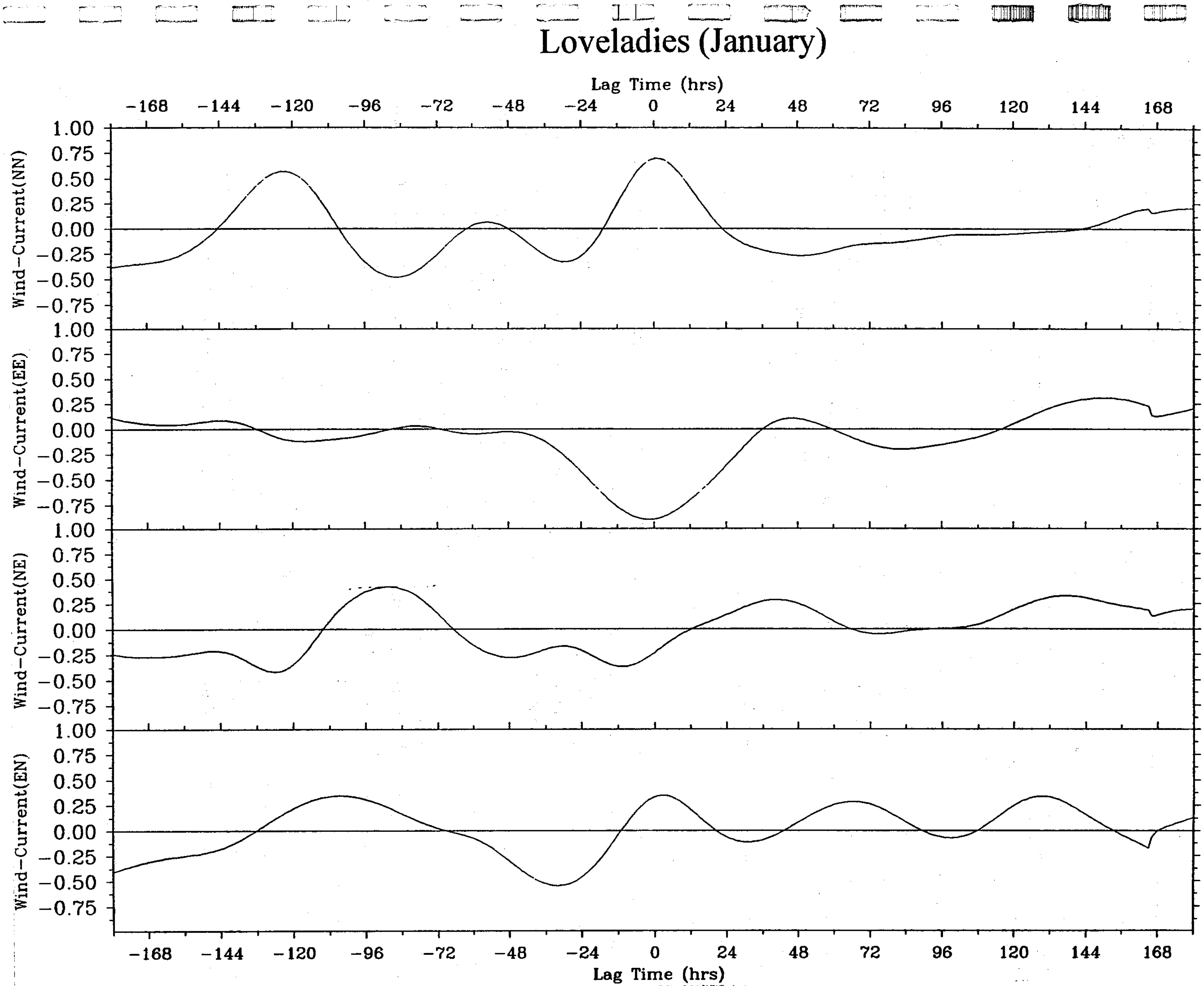



Figure 8-19. Cross-correlation between wind and current at Loveladies, January 1995.

## 8.6. Analysis of Marsh-McBirney Current Velocity Data

The exact locations of the Marsh-McBirney current velocity meters relative to the S-4 instruments are shown in Fig. 8-20. To detect possible two-layer current structure in the vertical direction, measured velocities at upper half depth and lower half depth were averaged. Typical time variations of upper layer current velocity and lower layer current velocity at Cedar Creek and Silver Bay locations are shown in Figures 8-21 and 8-26, respectively. For each location, the original vertical velocity distributions at two time instances are also shown (Figs. 8-22 and 8-23, Figs. 8-27 and 8-28). For comparisons, S-4 current data at nearby locations and wind data are also shown (Figs. 8-24 and 8-25, Figs 8-29 and 8-30).

The Marsh-McBirney current velocity data reveal the wind-induced two-layer current structure in the east-west orientation; this is consistent with the results of time series analysis of S-4 current data. The wind induced two-layer current structure in the north-south direction, if it exists, is combined with the tidal current, and is not easily detectable. For the same reason, the wind-induced horizontal circulation pattern, if it exists, is not easily detectable either. Because velocity measurements with the Marsh-McBirney current velocity meter were conducted only for a short period of time (less than a tidal cycle), it is difficult to separate the tidal current as was done for the long-term S-4 data.

## 8.7. Analysis of ADCP Current Velocity Data

ADCP measurements of current velocity distribution in four cross sections (transects) within the Bay were conducted on June 8, 1995 by U.S. Army Corps of Engineers to assist Rutgers' hydrographic study. Barnegat Bay is a very shallow bay for ADCP applications. However, we did manage to obtain some data. The current velocity contours of the Silver Bay transect are shown in Figures 8-31 and 8-32. Velocity vectors along the ship track are shown in Figure 8-33. Vertical velocity distribution at one time instance and at one location was shown in Fig. 8-34. For comparisons, wind data on June 8th, tidal elevation, and S-4 current data at a nearby location are shown in Figures 8-35 to 8-37. The current is generally toward the south. During the time interval of ADCP measurements, it is ebb tide and wind is toward the south-west, but weak. The combined action of tide and wind was driving flow toward the south. There was a slight flow reversal at the bottom toward the north; this may show a two-layer current structure induced by the southward wind.

The U.S. Army Corps of Engineers also conducted ADCP measurements at three transects at Barnegat Inlet to monitor the impacts of the south jetty modification. A relevant significant finding (Seaburgh, 1995) was the non-existence of the two-layer current structure caused by a density gradient at the Inlet, indicating a vertically well-mixed condition.

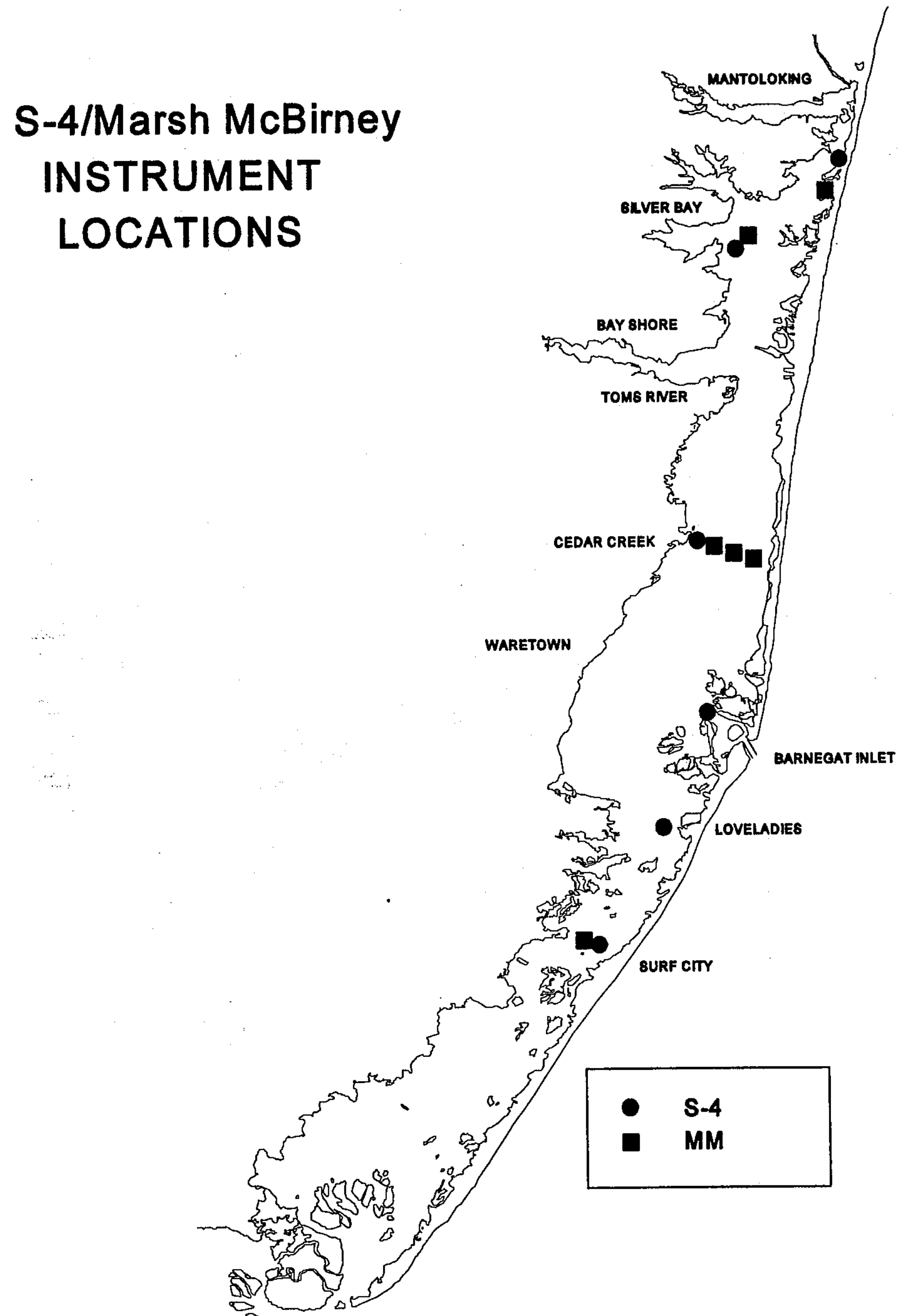
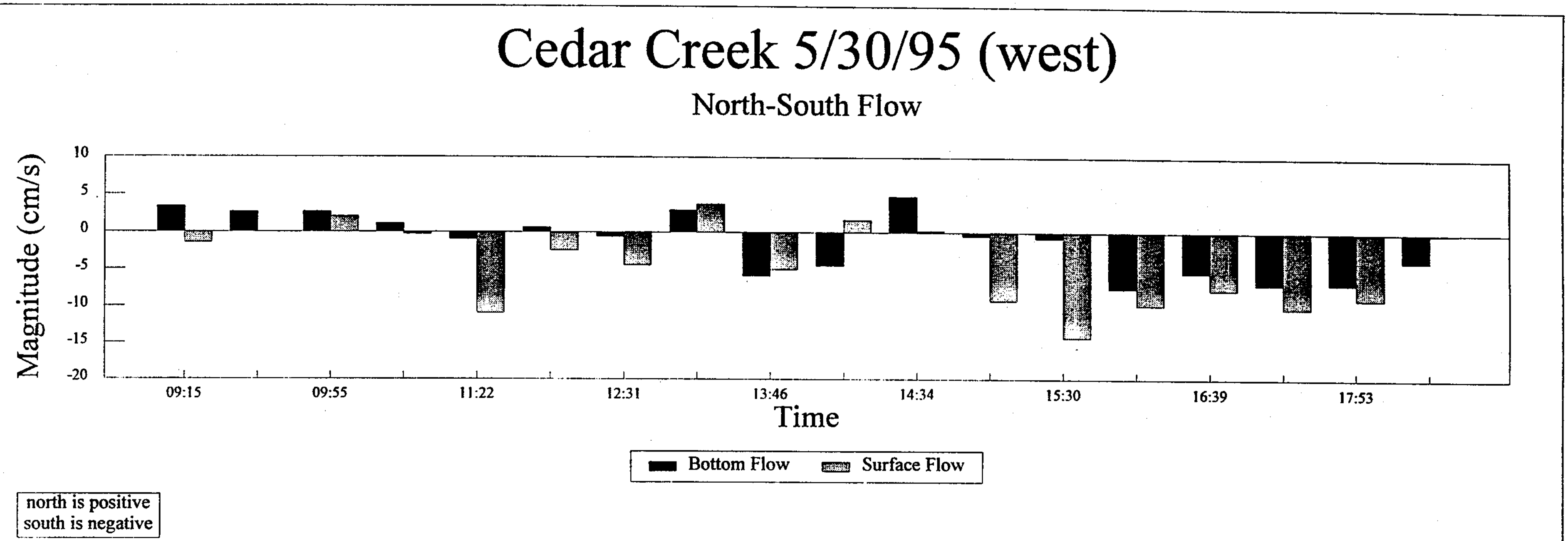



Figure 8-20. Map of Barnegat Bay showing locations of S-4 and Marsh McBirney instruments



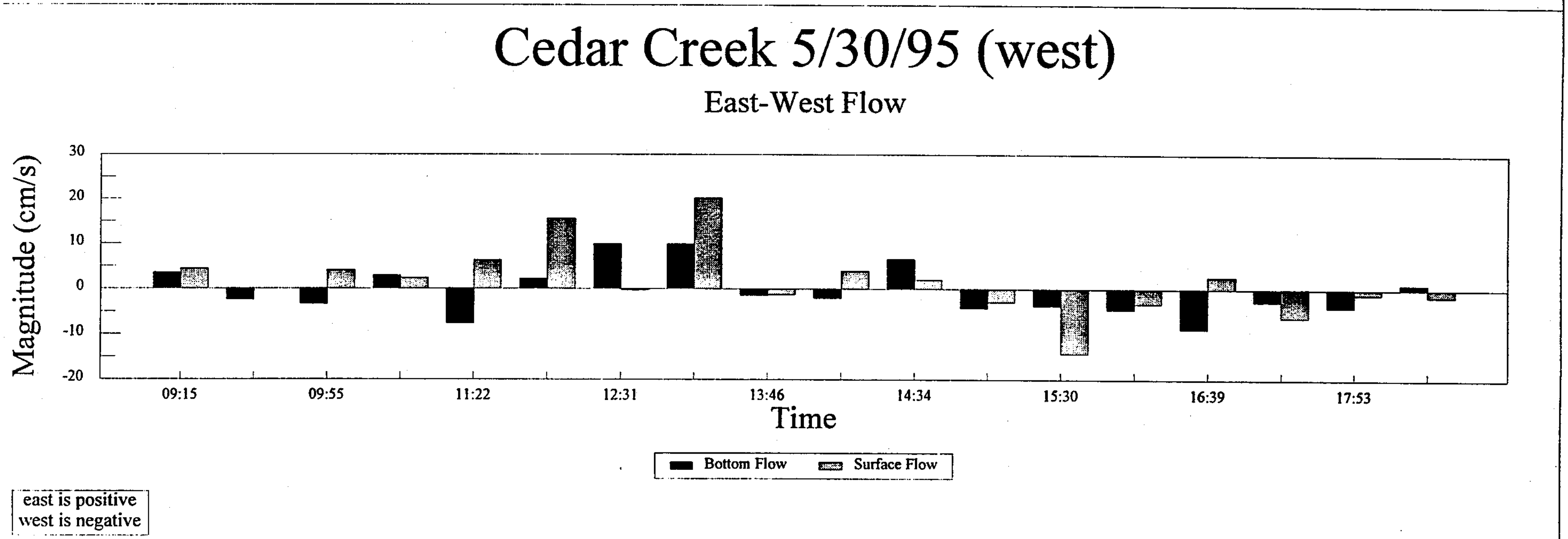




Figure 8-21. Temporal variation of upper layer and lower layer current velocity at Cedar Creek, 5/30/95

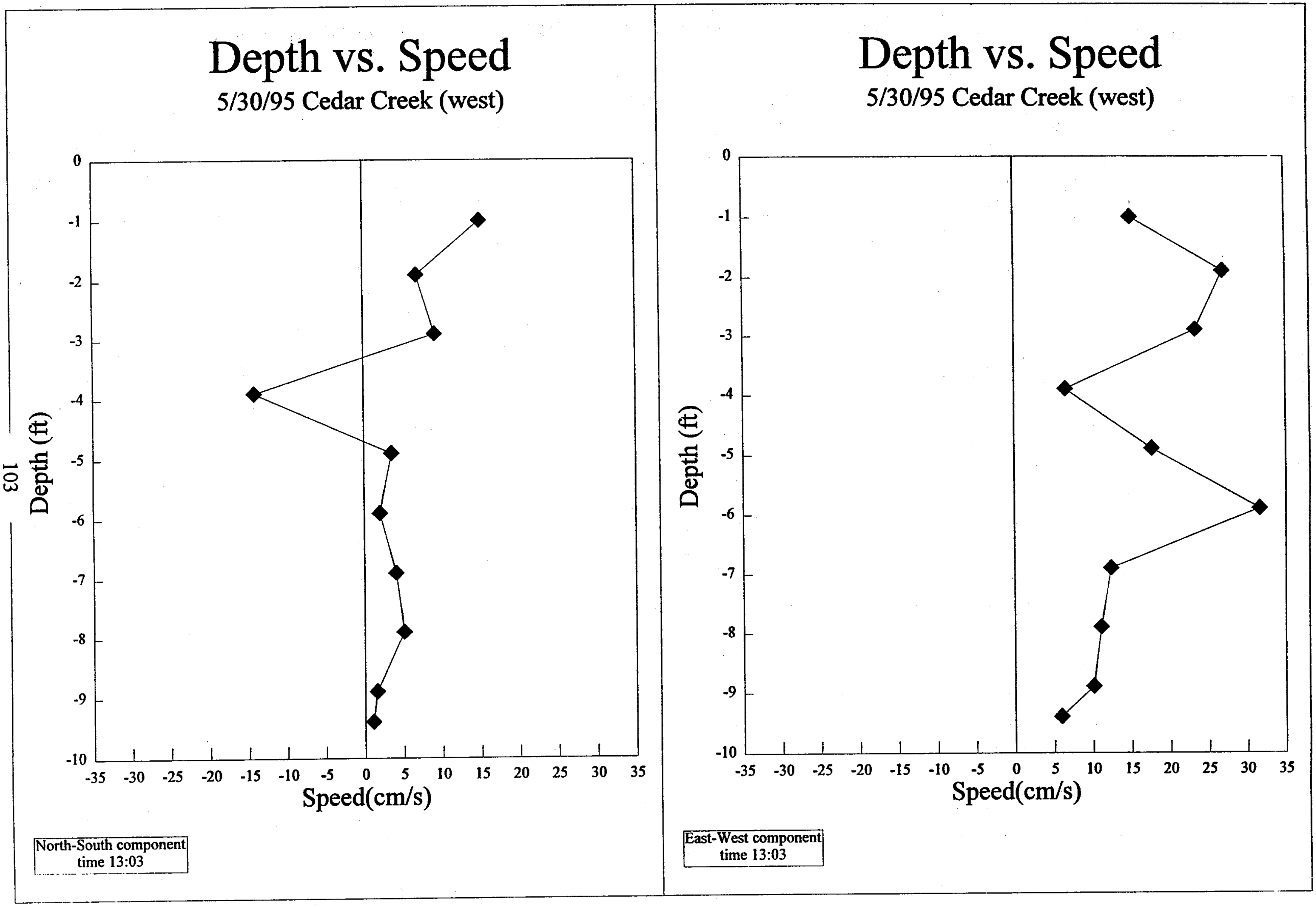



Figure 8-22. Vertical velocity distribution at Cedar Creek (North-South and East-West components), 1303, 5/30/95

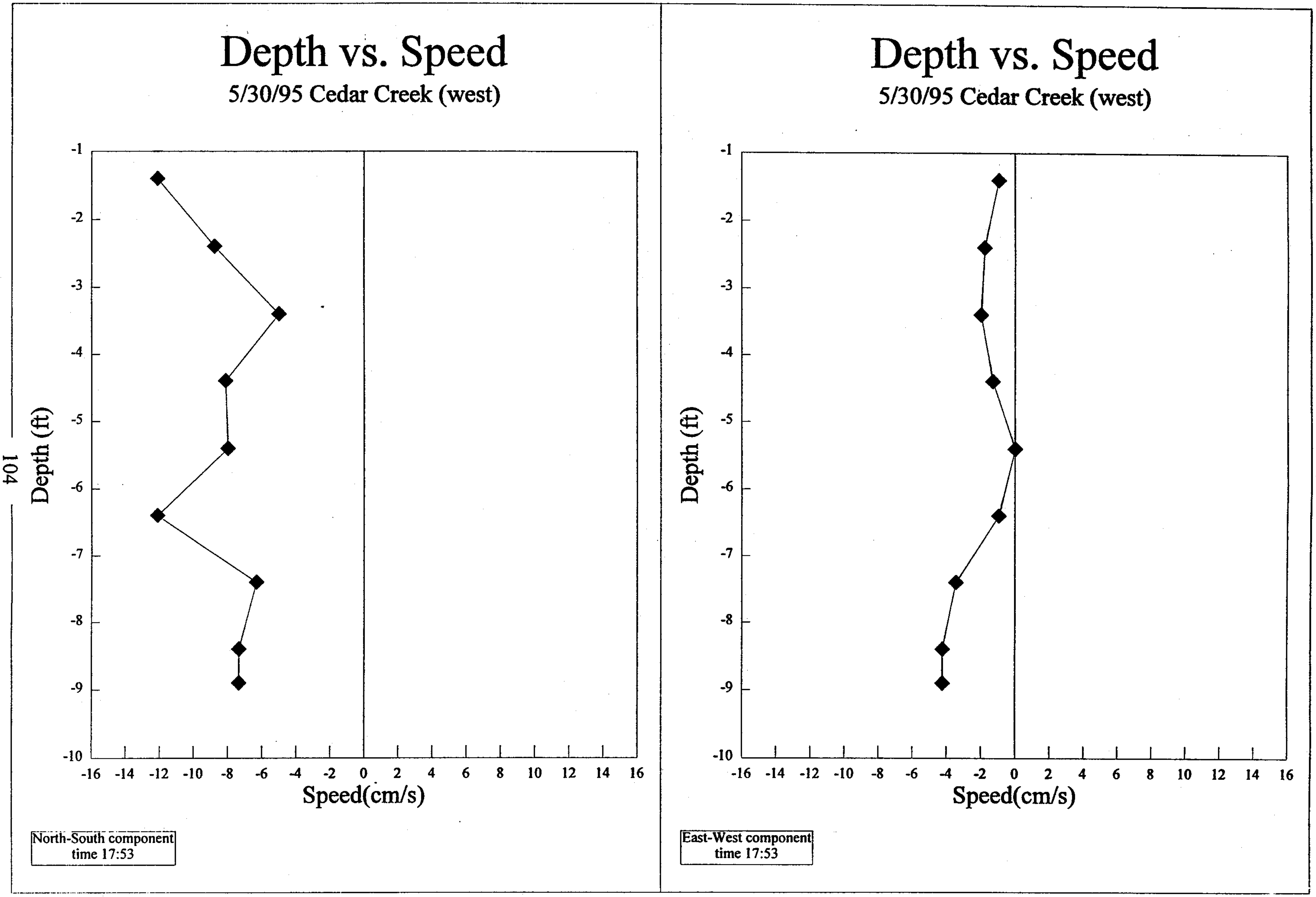
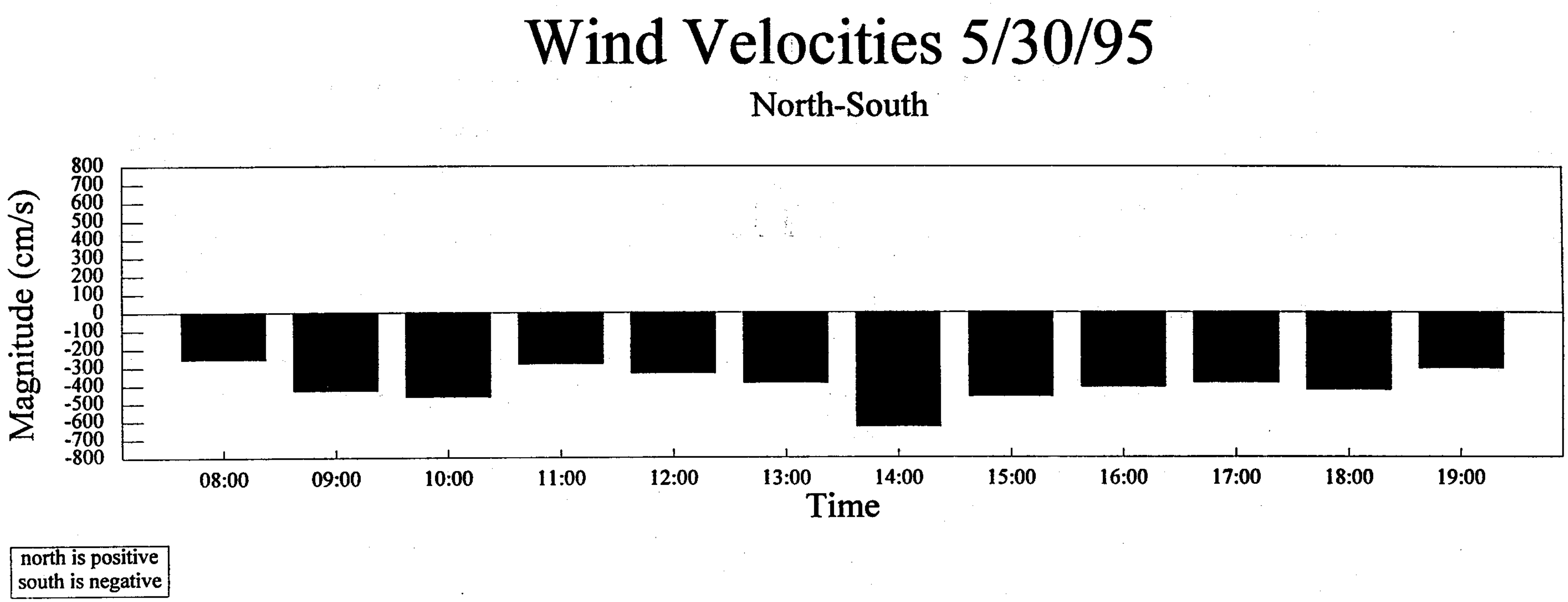



Figure 8-23. Vertical velocity distribution at Cedar Creek (North-South and East-West components), 1753, 5/30/95



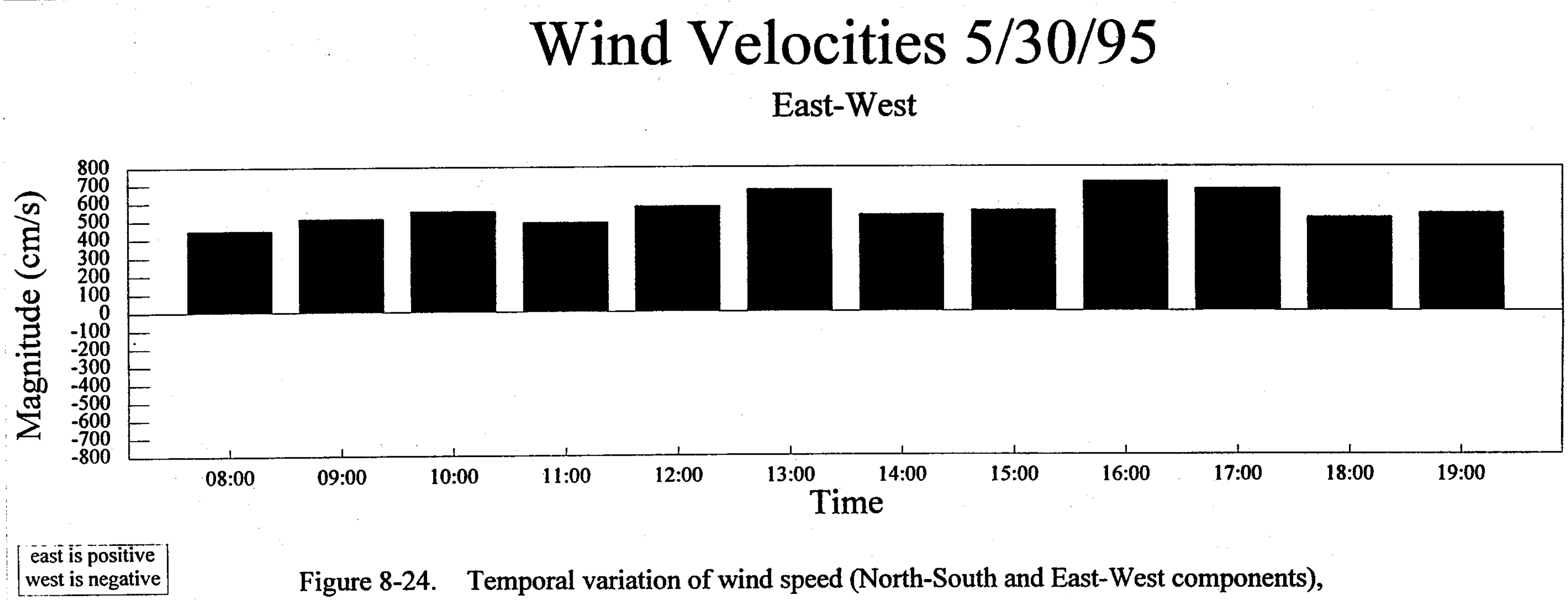




Figure 8-24. Temporal variation of wind speed (North-South and East-West components), 5/30/95.

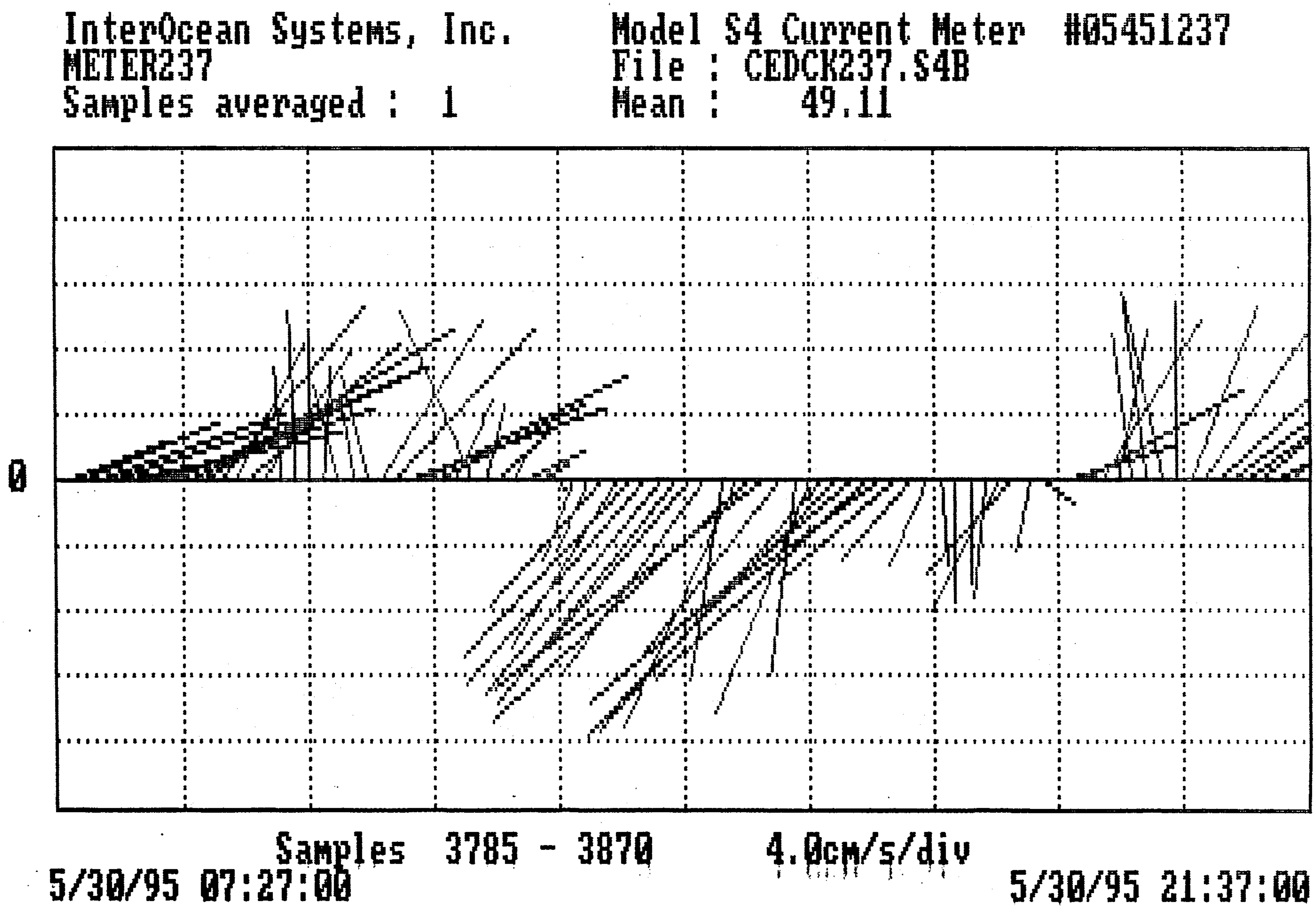
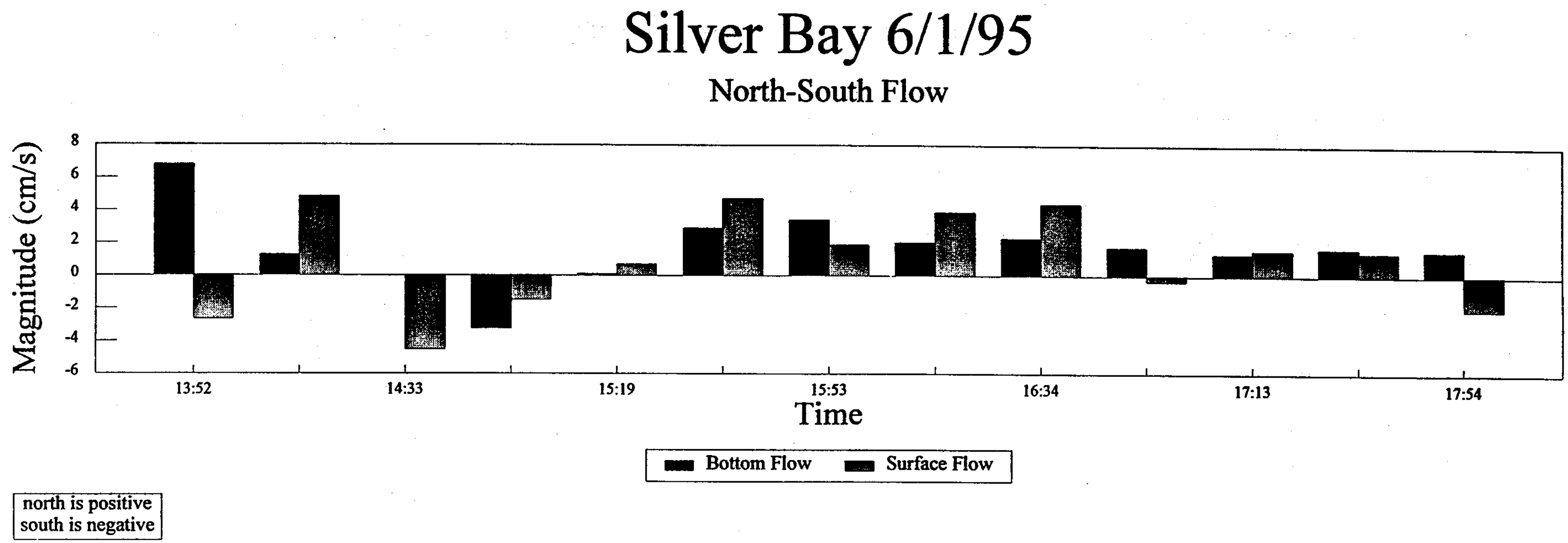



Figure 8-25. Straw diagram showing current magnitude and direction from S-4 instrument at Cedar Creek, 5/30/95.



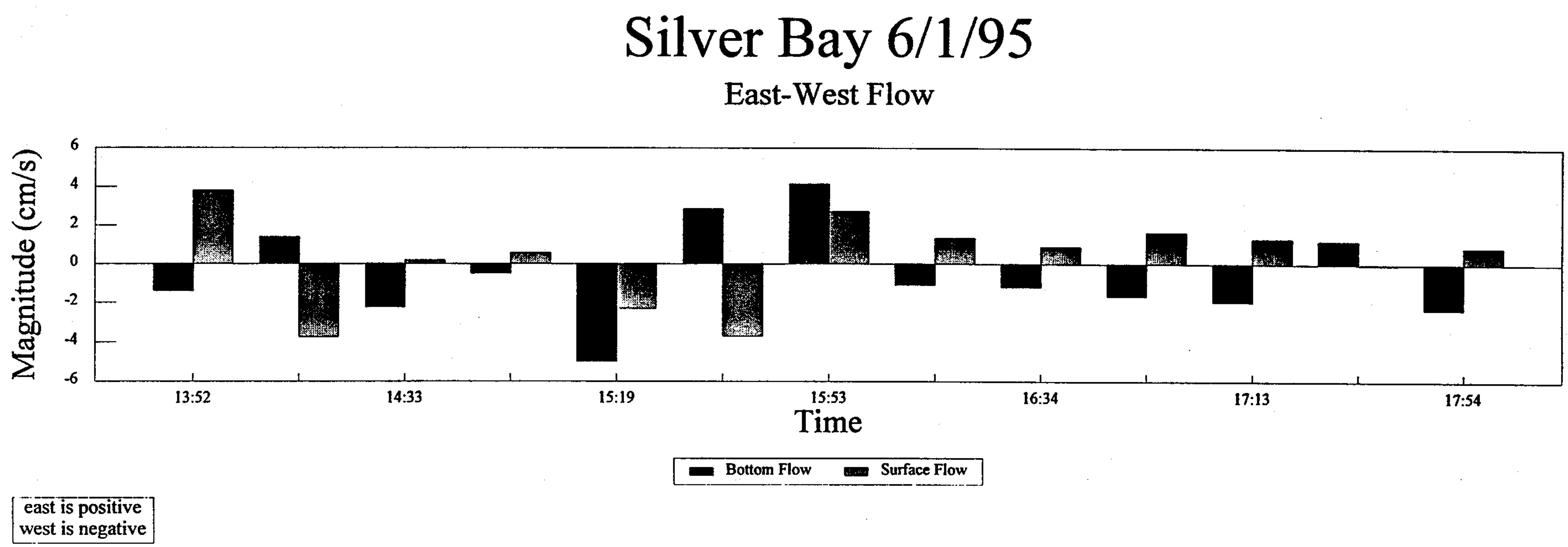




Figure 8-26. Temporal variations of upper layer and lower layer current velocity (N/S and E/W components) at Silver Bay, 6/1/95

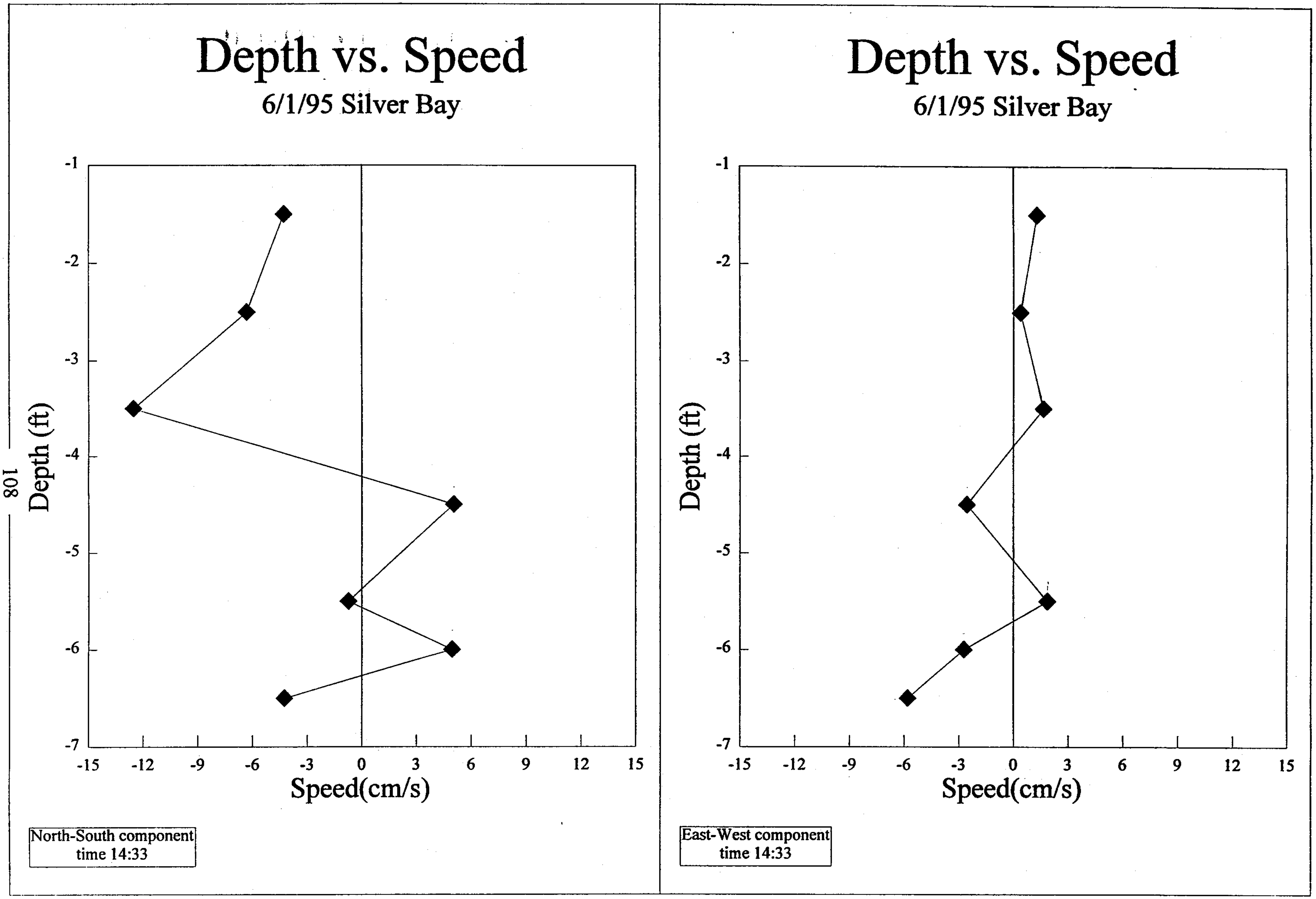



Figure 8-27. Vertical velocity distribution at Silver Bay (North-South and East-West components), 1433, 6/1/95

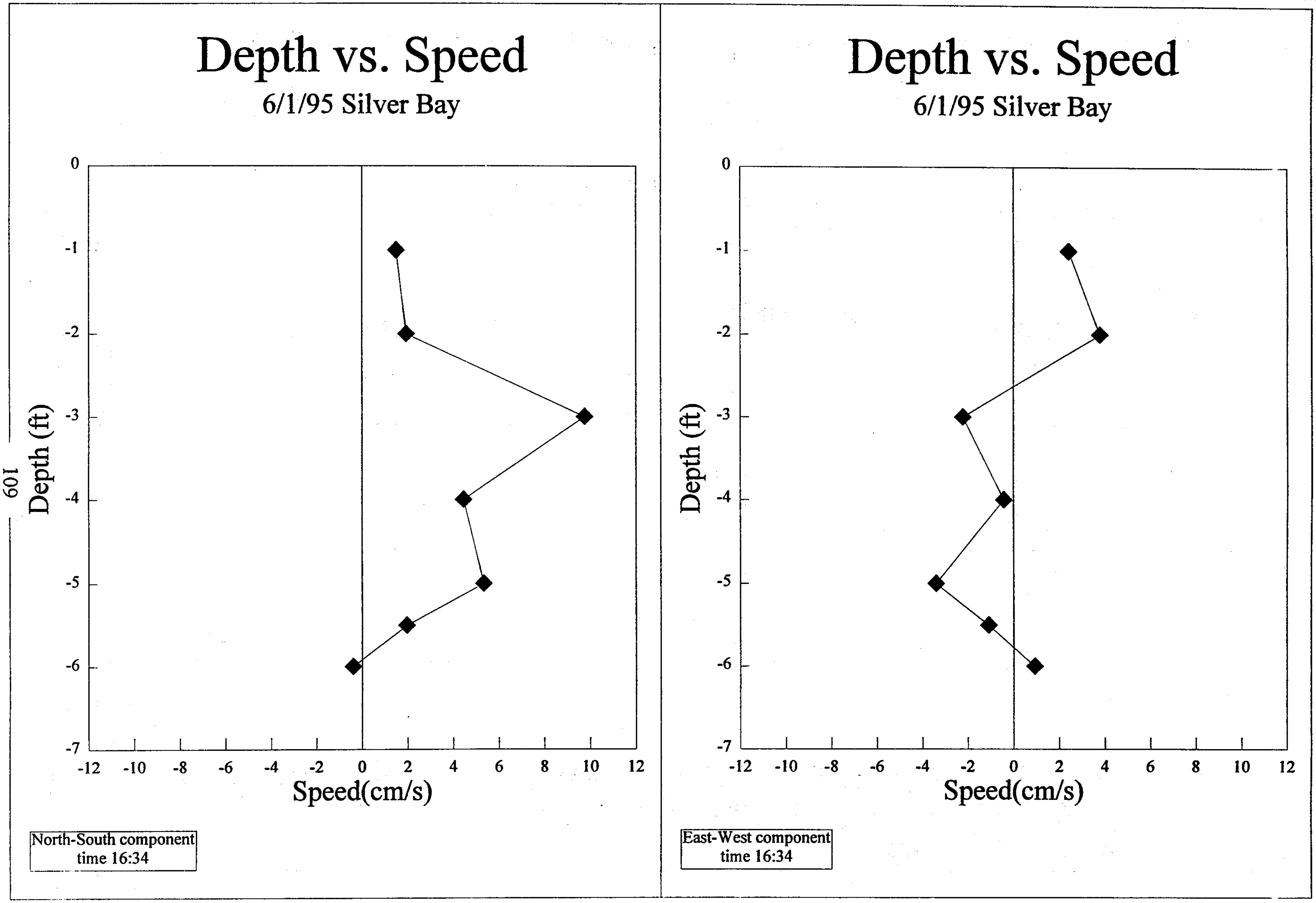



Figure 8-28. Vertical velocity distribution at Silver Bay (North-South and East-West components), 1634, 6/1/95

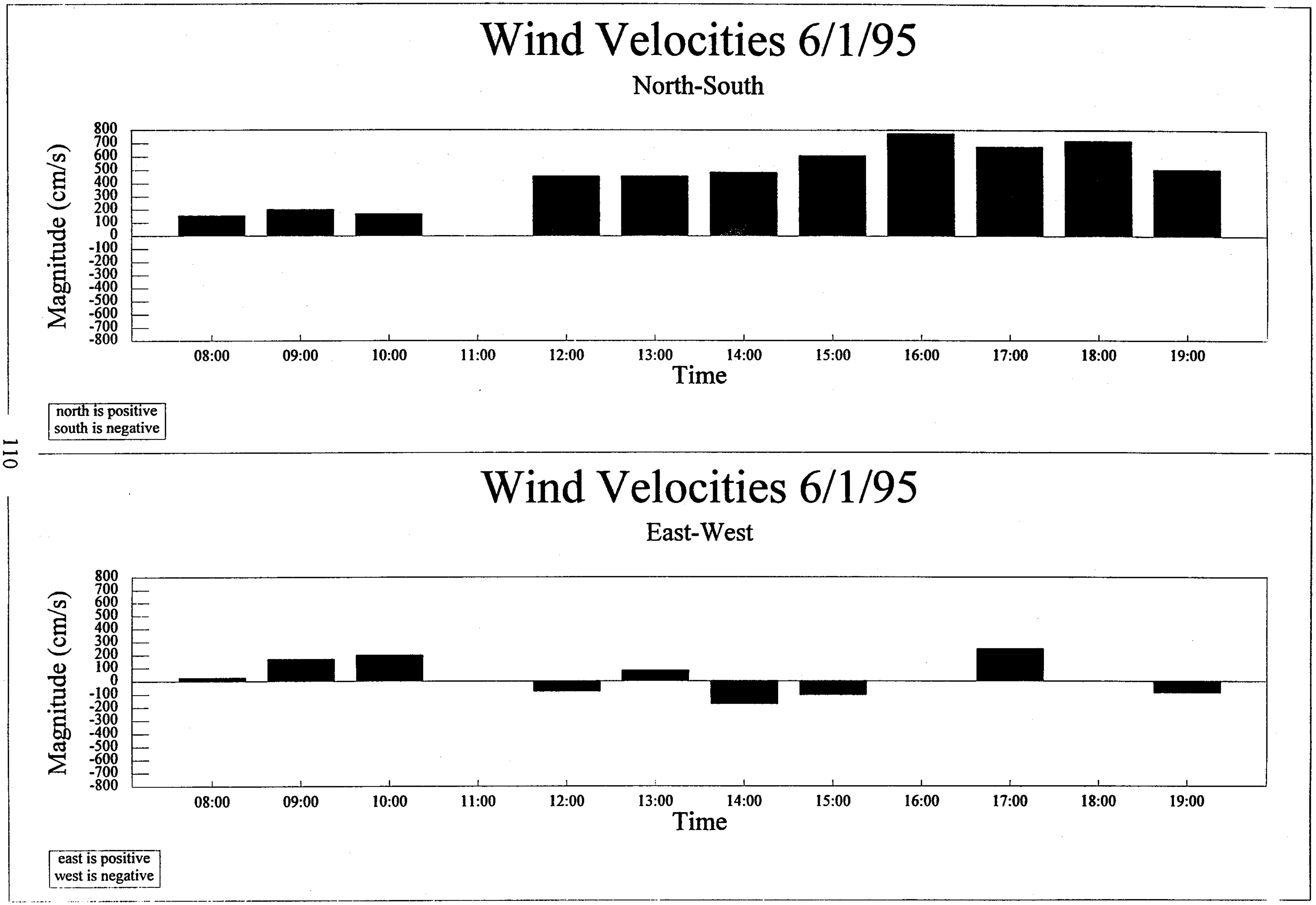





Figure 8-29. Temporal variation of wind speed (North-South and East-West components), 6/1/95

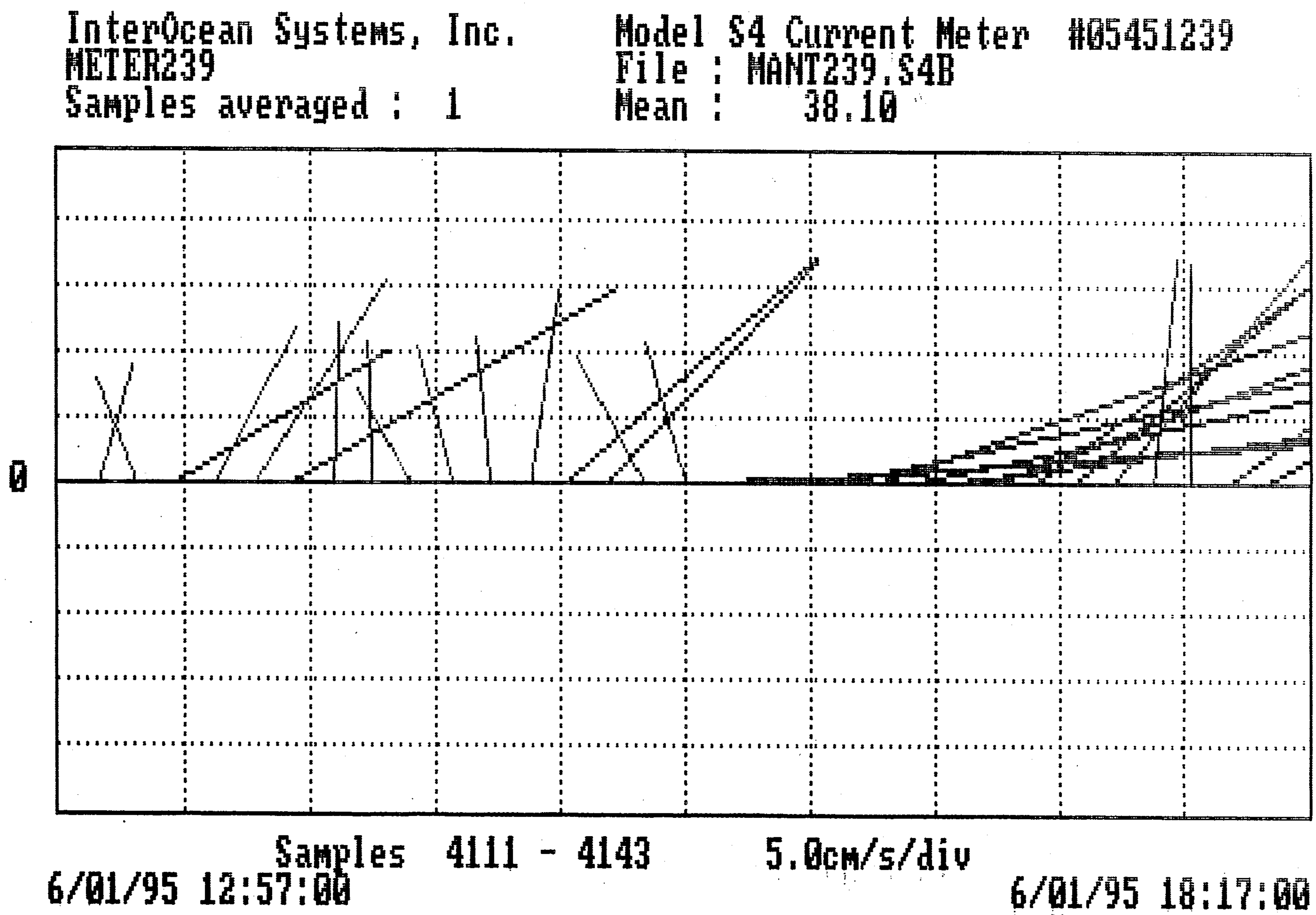



Figure 8-30. Straw diagram showing current magnitude and direction from S-4 instrument at Silver Bay, 6/1/95.

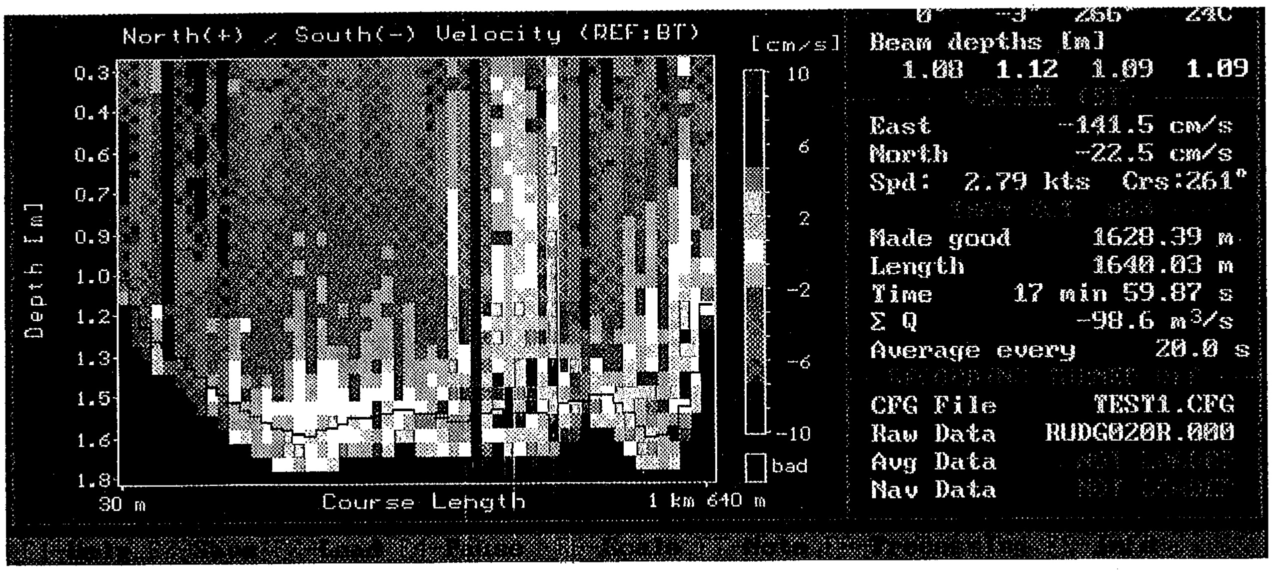



Figure 8-31. Silver Bay ADCP North-South velocity contour, 1408-1426, 6/8/95.

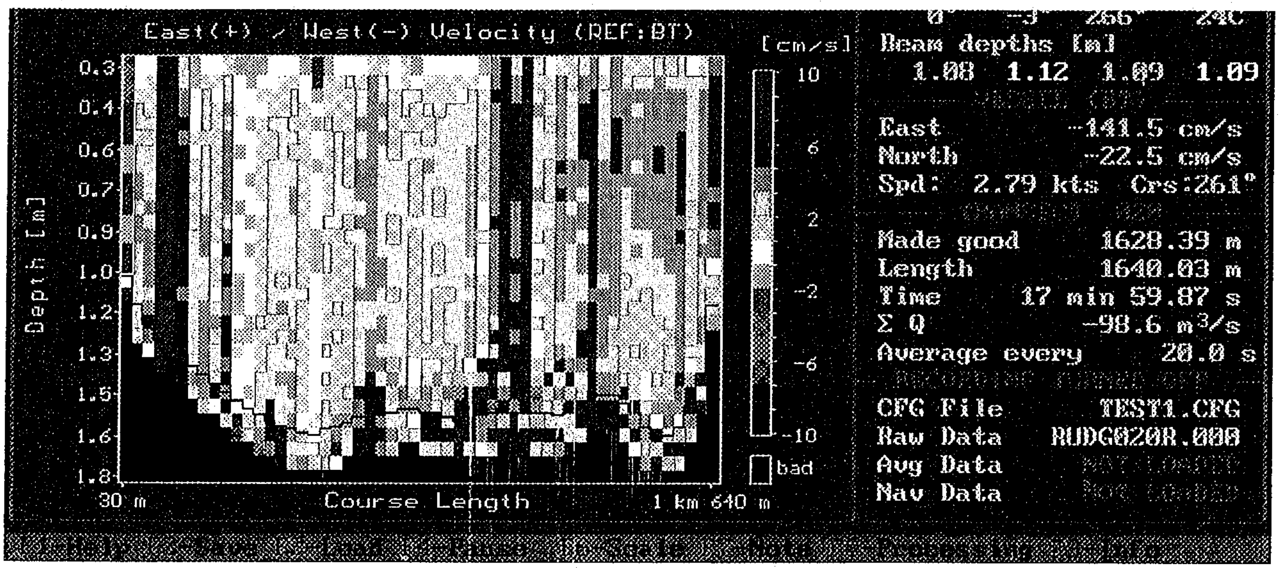



Figure 8-32. Silver Bay ADCP East-West velocity contour, 1408-1426, 6/8/95.

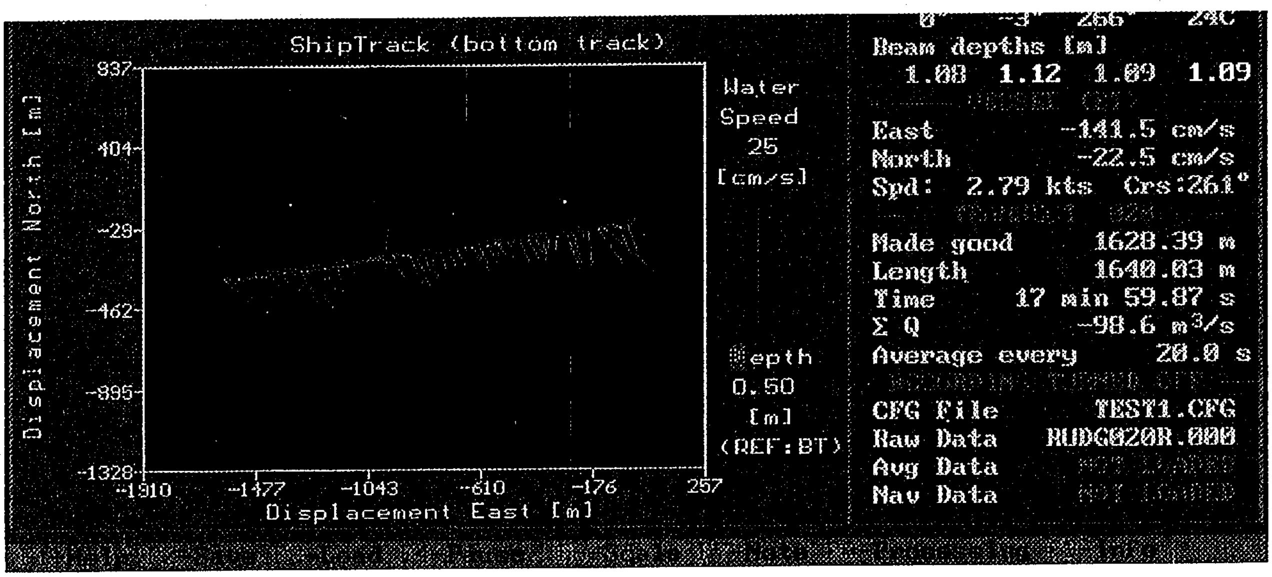



Figure 8-33. Silver Bay ADCP ship track and current velocity vector, 1408-1426, 6/8/95.

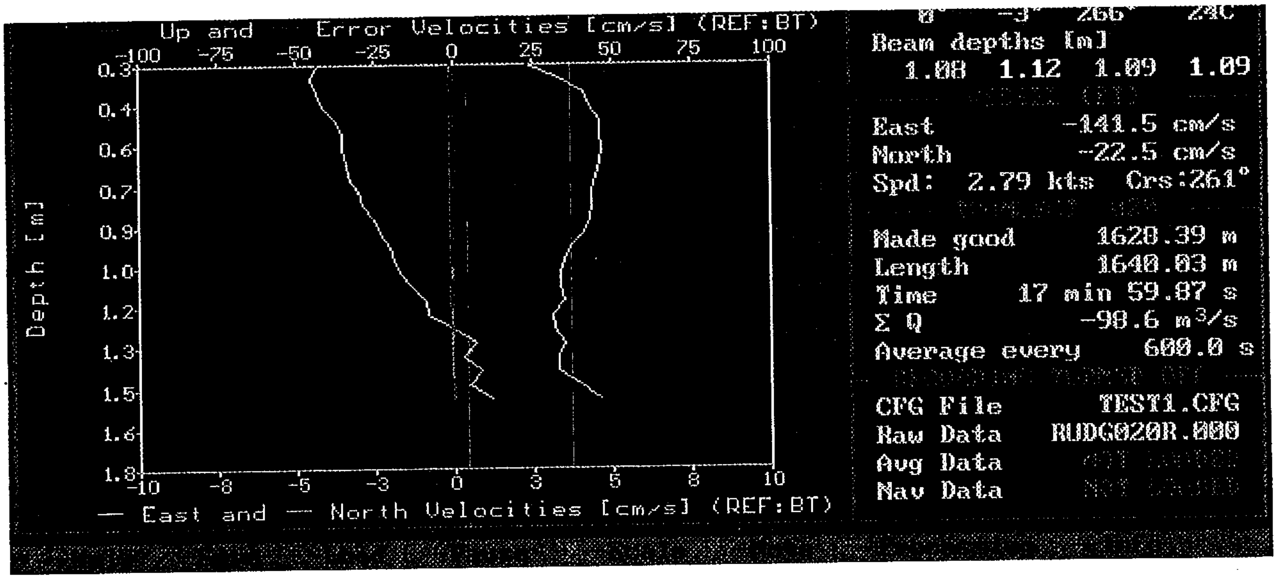



Figure 8-34. Silver Bay ADCP vertical velocity profile, 6/8/95.

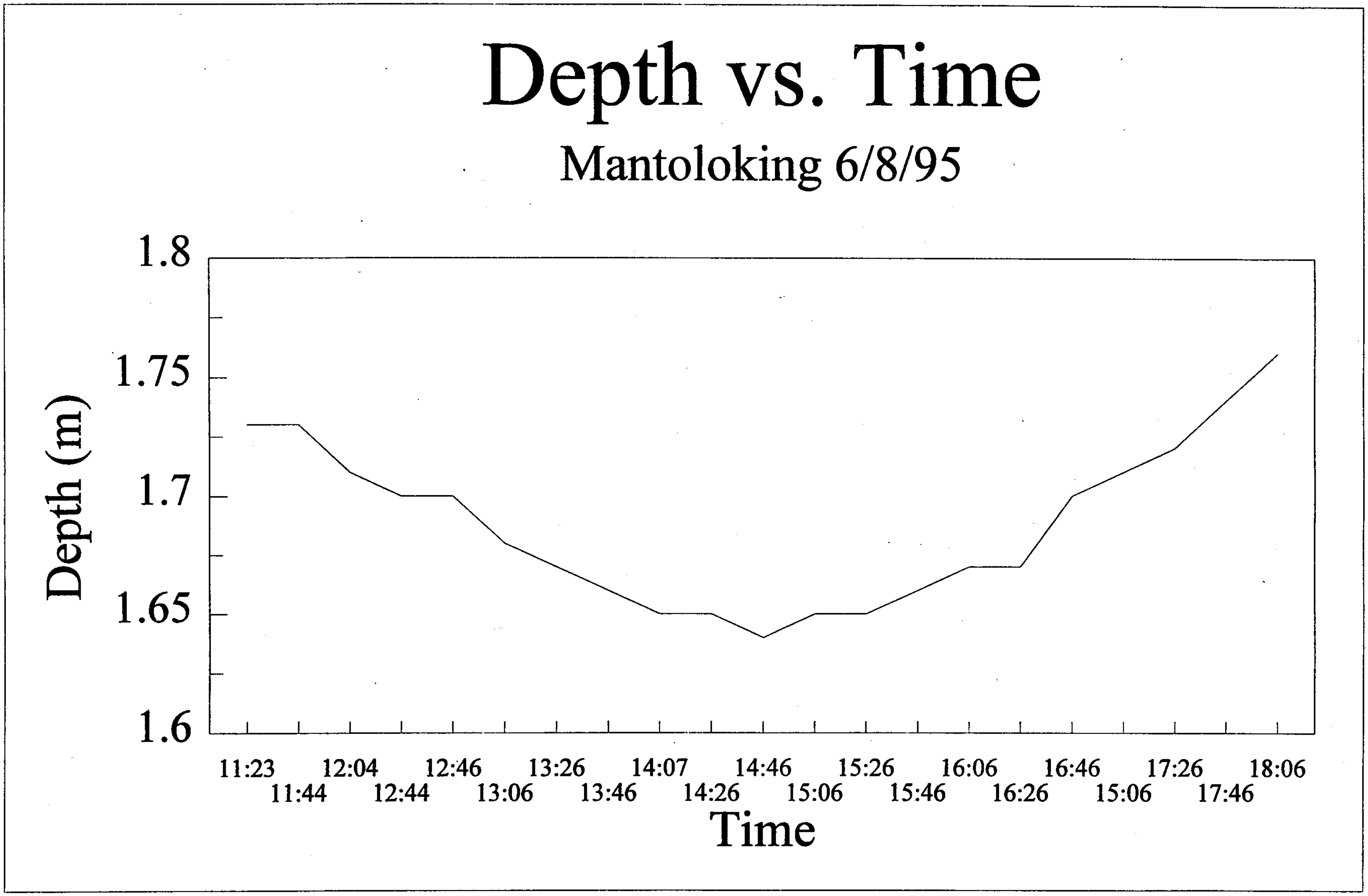
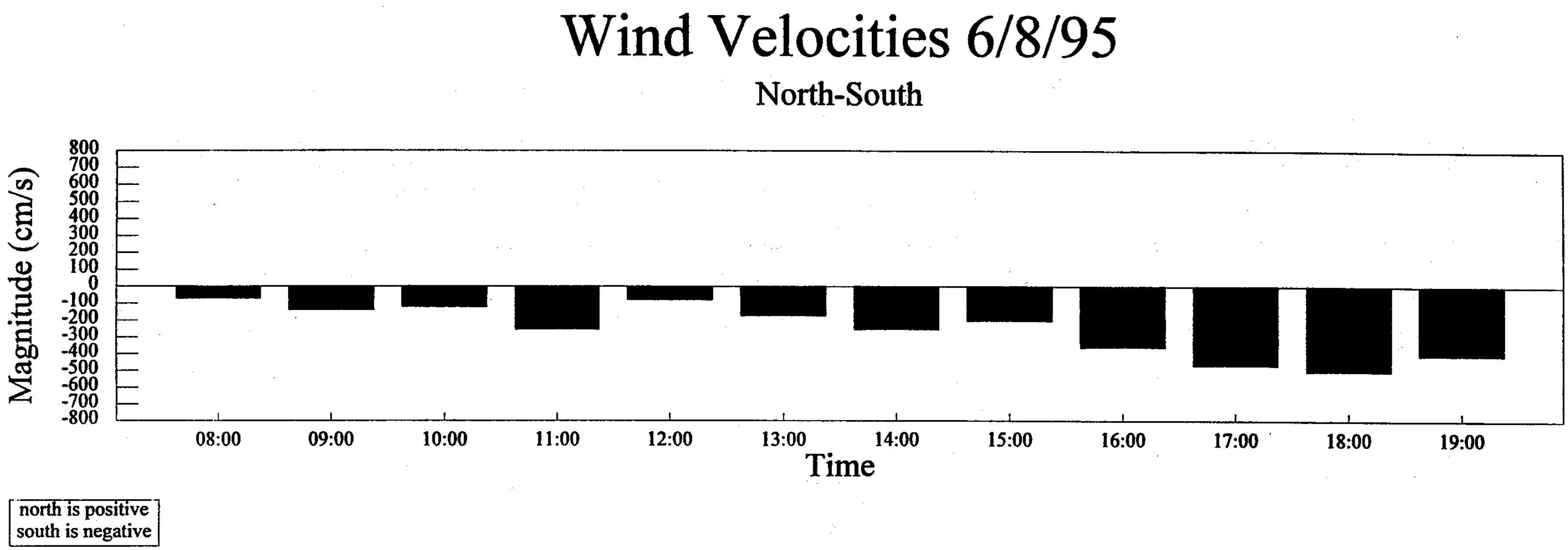



Figure 8-35. Water surface elevation at Mantoloking visually read from stadia rod, 6/8/95



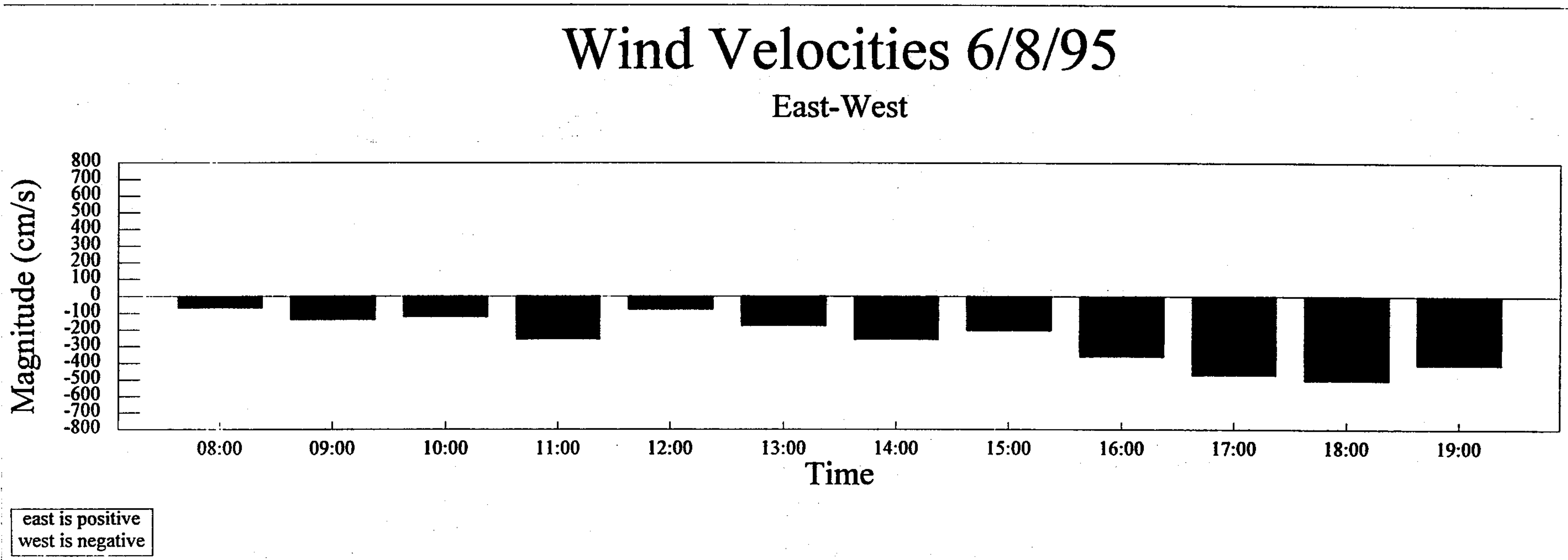




Figure 8-36. Temporal variations of wind speed (North-South and East-West components), Atlantic City, 6/8/95

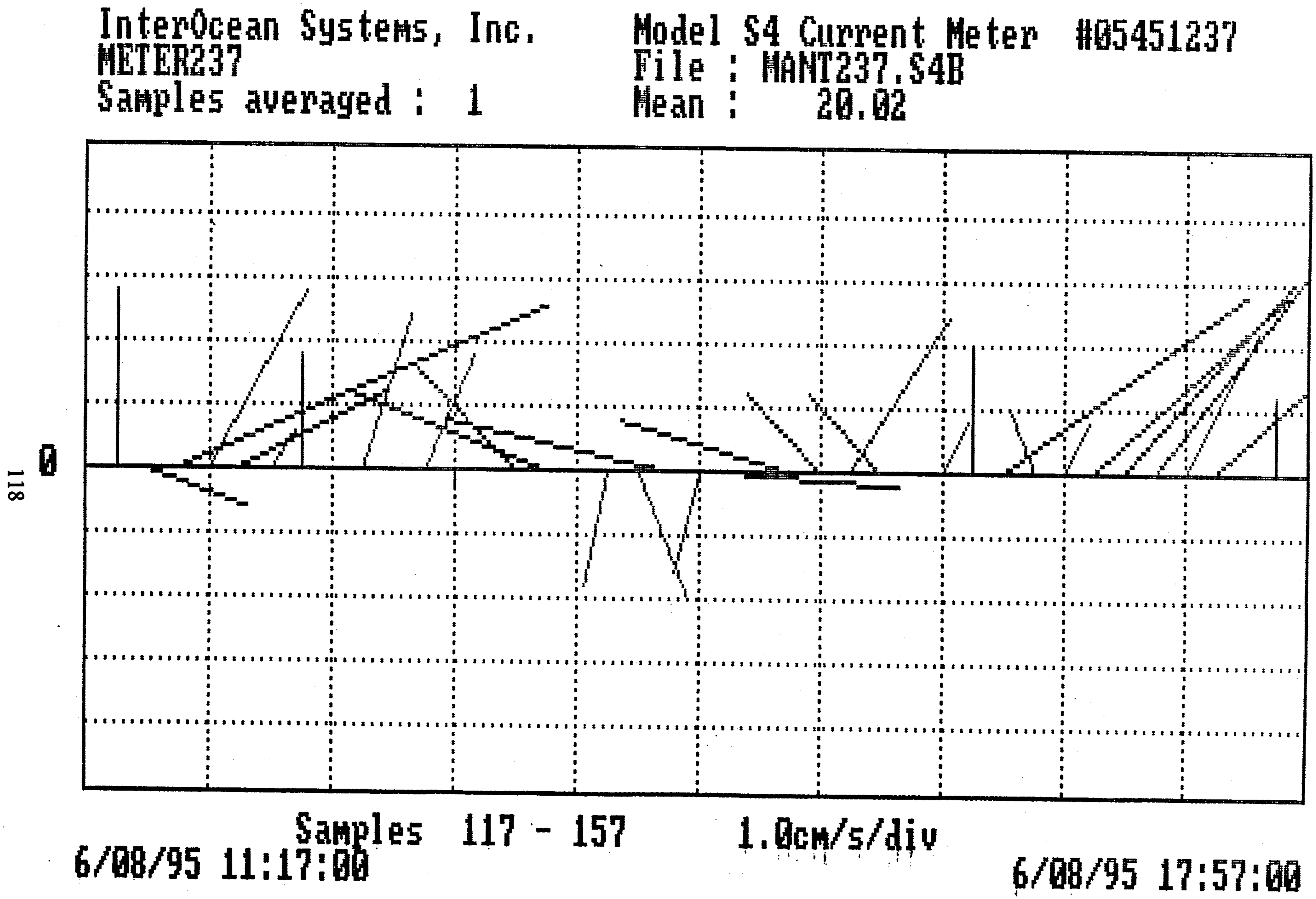



Figure 8-37. Straw diagram of current speed vectors from S-4 instrument at Mantoloking on 6/8/95.

## 8.8. Summary of Circulation Pattern of Barnegat Bay

### 8.8.1. Tidal Flushing Time

The average tidal flushing time was estimated to be approximately 58 days. The flushing time was calculated using the continuous salinity data at Barnegat Inlet obtained by this hydrographic study. The tidal exchange rate was calculated first and then it was used to calculate the flushing time. On the average, sixty three percent of water entering the Bay on the flood tide leaves the Bay on the following ebb tide without diluting pollutants in the Bay.

Based on the estimated flushing time, it is concluded that direct ground water seepage into the Bay is relatively small, which is in agreement with U.S.G.S.'s rough estimate using a three-dimensional ground water model.

### 8.8.2. Horizontal distribution of salinity and temperature

There exists a horizontal salinity gradient in the Bay, highest near the Inlet, lowest at locations away from the inlet and adjacent to surface streams. Temperature is quite uniform in the horizontal plane in summer, whereas there is a spatial variation in the winter.

### 8.8.3. Vertical distribution of salinity and temperature

Salinity is generally quite uniform in the vertical direction, except at areas close to the Inlet during flood tide. Temperate is uniform in the vertical direction. These data indicate that Barnegat Bay, in general, is well-mixed in the vertical direction.

### 8.8.4. Flow pattern (circulation pattern)

The flow generally follows the north-south orientation of the Bay. In the south and middle portions of the Bay, the north-south current is dominated by tidal influence; however, wind is inducing a two-layer (surface-bottom) current structure in the east-west orientation. Existence of the two-layer current structure accelerates pollutant mixing from west to east and discharging to the ocean.

In the northern portion of the Bay, due to its far distance from the inlet and its shallowness, the wind is the dominant driving force. The wind is inducing the two-layer current structure in both the east-west orientation, and in the north-south orientation. Pollutants introduced into this portion of the Bay will be mixed faster than those in the southern and middle portions of the Bay.

## 9.0 Preliminary Recommendations on Numerical Circulation Models

The major assumptions and applicabilities of models of various dimensions were summarized in Table 4-2 and described in Section 4. To describe the circulation pattern properly, a two-dimensional depth-averaged model is preliminarily recommended. The strong influence of wind on the circulation pattern, especially in northern portion of the Bay, was preliminarily quantified through this research project. If further field data collection confirms this finding, application of a layered version of the three-dimensional model may be necessary for simulating Barnegat Bay.

A zero-dimensional model, such as tidal exchange model, can be applied to obtain a mean condition for the entire Bay, for example, pollutant flushing time for the entire Bay. Information for a mean condition is valuable as it considers the overall bay condition, such as total watershed nutrient contribution versus total ocean nutrient contribution. Continuous salinity data collection at Barnegat Inlet reveals that, on average, only thirty seven percent of the ocean water entering on the flood tide is new ocean water. This number is very important in determining amount of nutrients contributed from the ocean. By applying the zero-dimensional model, this number is also very important in determining the amount of direct ground water seepage into the Bay. The direct ground water seepage was calculated to be relatively small, thus, nutrient contribution from this source is also very small.

A one-dimensional model can be used to generate information about the down-stream gradients. It is an advance on the previous model because it can recognize that the Bay is not fully mixed in the horizontal plane and thus it can provide a more realistic rendition of the differences within the Bay.

However, only a two-dimensional depth-averaged model can provide sufficient spatial information that can accommodate exchanges through the length of the Bay and across the Bay, thereby, identifying inputs of individual watersheds and mixing within the tidal basin. Our newly gathered field data reveals that the Bay is not fully mixed in the horizontal plane. Consequently, managing Kettle Creek, for example, will mostly affect water quality in northern portion of the Bay. We like to have a model which distinguishes between the northern portion and the southern portions of the Bay. Also, management of the entire Bay's watershed will mostly affect the western portion of the Bay. We like to have a model which will also distinguishes between the western and the eastern portions of the Bay. Thus, a two-dimensional model is necessary to incorporate the several gradients and mixing directions and to relate to management decisions.

Fortunately, our field data reveal a well-mixed condition in the vertical direction. From this point of view, a three-dimensional model is unnecessary. However, if wind indeed induces a strong layered current structure on the vertical plane, which not only makes mixing faster in the vertical plane, but also in the horizontal plane, it may be necessary to use a three-dimensional model to solve for the layered-current structure in the vertical plane to improve the simulation of mixing in the horizontal plane. The knowledge of horizontal mixing is especially important because it leads to an ability to quantify inputs and effects of individual sub-watersheds (e.g., Toms River) on portions in the Bay and the entire Bay. Obviously, this is a major management objective.

Recommendation for two-dimensional depth-averaged models and consideration of layered version of three-dimensional models are further described below.

### 9.1. Recommendation for two-dimensional depth-averaged models

A two-dimensional depth-averaged circulation model is recommended for Barnegat Bay at this stage. However, due to the existence of a two-layer current structure induced by wind, especially in the northern portion of the Bay, two factors during application of the depth-averaged models must be considered:

a. In the hydrodynamic component of the model, the Manning's coefficient is no longer purely dependent on bottom roughness and the water depth. It will also vary with wind speed and magnitude.

b. In the mass transport component of the model, the dispersion coefficients will be much larger than those purely caused by tidal current, and they will vary with wind speed and direction.

Through this hydrographic study, sufficient data has been collected to drive, calibrate, and verify a two-dimensional depth-averaged model. However, the wind is strong and it varies with the seasons. The coefficients calibrated with winter data are most likely not applicable in the summer season. If this is the case, the model is not completely verified. In this sense, a diagnostic run of a two-dimensional depth-averaged model is recommended to further confirm the doubts which are raised by the field data collection and analysis.

To use the two-dimensional depth-averaged model, and to reduce uncertainties in model calibration and verification, it is recommended that additional local current data be collected and dye tests conducted to establish the general relation between the wind and the Manning's bottom resistance coefficient and the dispersion coefficients.

There are many two-dimensional depth averaged-models available, for example, TABS-2, TRIM, and the 2-D version of CH3D. Before application of any existing models, an in-depth study of the model is recommended. Because of the necessary detailed understanding of a particular model, in many cases, personal experience becomes the determining factor.

## 9.2. Consideration of Layered Version of Three-Dimensional Models

A layered (for example, two layers) version of three-dimensional model, as reviewed in section 4.6.1., should also be considered for Barnegat Bay because of the strong wind effect. A layered version of the three-dimensional model can be used to solve for the two-layer current structure directly, thus disassociating the wind and calibration coefficients. However, additional data on two-layer current structure, for example, using two current velocity sensors in the vertical direction for a long-term period of time at the boundary and within the Bay must be collected to properly calibrate and verify a layered version of the three-dimensional model. In the hydrographic study reported here, only one current velocity sensor was used in the vertical direction, largely due to the budget constraint. It should be noted that the data collected thus far are enough to drive, calibrate, and verify a two-dimensional depth-averaged model, which the model is most likely applicable to Barnegat Bay.

# 10.0 Recommendations on Future Studies

## 10.1. Further Field Data Collection

### 10.1.1 The Second Year Hydrographic Data Collection

- Introduction

The proposal for the second year hydrographic data collection has already been submitted to the U.S. Environmental Protection Agency, Region II, through NJDEP. The scope of work is included herein for reference.

The proposed extension of the Barnegat Bay Hydrographic Study into the second year is designed for additional field data acquisition that would greatly facilitate the hydrodynamic/mass transport model formulation and its subsequent applications and provide: (I) better understanding of the relative importance of wind-induced and tidally-driven flows in Barnegat Bay that, in turn, would further refine modeling approaches; (ii) assessments of dispersion and other parameters needed for model formulation; (iii) an extensive data base that will be used for calibration and verification of the depth-averaged numerical hydrodynamic and mass transport model if it is adopted. A hydrodynamic and mass transport model will provide temporal and spatial variations of surface elevations, current velocities, temperature, and salinity within the Bay under known driving forces and boundary conditions. A properly calibrated and verified hydrodynamic and mass transport model is a prerequisite to predicting pollutant fate and transport within the Bay. This information will assist in development of management scenarios for environmental protection of the Bay.

- Rational for Additional Field Data Collection

The field data collection plan during the first year of the project was designed to meet the budget constraints of the NJDEP. As a result, the field data acquisition was based on rather simplified wind drift/tide circulatory interaction mechanisms that might not exactly reflect the real world. During the first year field data collection and analysis, we came to realize that the following additional field data are needed for reduction of uncertainties in future model development:

a. The wind stress causes such complex circulation patterns that long-term spatial measurements of velocity profiles are needed to define wind-induced and tidal effects.

Additional field data collection is necessary to verify our original assumptions that (1) the shallowness of Barnegat Bay causes vertical velocity gradients and strong turbulence, which, in turn, are responsible for its vertical property homogeneity; and (2) the shallowness of the Bay causes only a horizontal residual circulation pattern no matter by wind, tide, or a combination of both. If these two assumptions correspond with reality, a depth-averaged model can be applied, and the field data collected during the first year of the project can be used to drive, calibrate, and verify the model. However, a strong, stationary wind could induce a two-layer (current-undercurrent) flow structure. If such a dynamic situation persists during typical wind events, characteristic for the Bay climatic conditions, the vertically-averaged hydrodynamic model can not be fully applicable; a three-dimensional model becomes a more suitable predictive tool instead. It worth mentioning that, a three-dimensional model requires not only much more computer capabilities but also much more detailed field data for calibration and verification.

Long-term spatial velocity profiles in both longitudinal and transverse sections will be needed in order to clearly delineate the wind-induced signals on the background of more regular tidally-driven motions, and thus to define the wind-induced circulation patterns. During the first year of the project, there was only one long-term S-4 current sensor at a prescribed position, whereas multiple sensors are needed. Some spatial measurements of velocity profiles along transverse vertical directions were made using Marsh McBirney current velocity meters and a ADCP (Acoustic Doppler Current Profiler) during the first year of the project. However, they were made for a short period of time (one or less than a tidal cycle), therefore, wind-induced effects were not fully seen on the background of currents of each origin.

If a depth-averaged two-dimensional hydrodynamic model is indeed proven to be appropriate through the observed current fields, these additional data will be used to establish numerical site specific relationships between the bottom shear stress and the depth-averaged velocity. In the depth-averaged model, used elsewhere, the bottom shear stress is usually related to depth-averaged velocity by conventionally assuming a logarithmic vertical velocity profile and leaving a bottom resistance coefficient for calibration. This assumption was proven adequate for unidirectional coastal currents. In the Bay, as several available current measurements in transverse vertical directions show, the vertical velocity profiles depart from the logarithmic curve because of perhaps combined actions of wind and tide. A relationship between the bottom shear stress and the depth-averaged velocity should be redefined to be included in the model.

<u>b. Uncertainty in fresh groundwater input requires fresh water and salinity balance analysis using the available and projected observations on river influx, currents, and salinity fields. This work is necessary to further confirm the validity of fresh groundwater input estimated by others.</u>

Dispersion or diffusion coefficients should be determined before we can use a two- or three-dimensional mass transport model for estimating the fresh groundwater input. The single-box approach was used for fresh water and salinity balance analysis during the first year of the project. An agreement was found between the total amount of fresh groundwater input estimated by U.S.G.S. and our estimate. However, we have only compared these two estimates for the entire bay, not spatially. A better confirmation is to use a two- or three-dimensional mass transport model for the spatial estimate, in concert with the hydrodynamic modeling approach to be determined. In the two- or three-dimensional mass transport model, there are two- or three-dispersion/diffusion coefficients. These dispersion/diffusion coefficients should be determined before we can use the two- or three-dimensional mass transport model for estimating the fresh groundwater input (Visa versa, if we want to use the measured current and salinity information to derive the dispersion/diffusion coefficients from the salinity balance equation, we must know groundwater input before-hand).

Dye tests, drifter tracking, or current velocity recording with a high degree of temporal and spatial resolution are needed to determine the dispersion/diffusion coefficients for the two- or three- dimensional transport model. Dye tests and drifter tracking seem to be more feasible for Barnegat Bay.

Field-determined dispersion/diffusion coefficients can not only be used to back calculate spatial direct groundwater input, but also to establish relationship between dispersion coefficients and wind for the application of a two-dimensional depth-averaged model.

- Objectives

a. Collect long-term velocity profile data to define the wind-induced and tidal effects, and to better define the relationship between bottom shear stress and depth-averaged velocities in the depth-averaged numerical hydrodynamic model. It is also necessary to prove or disapprove the application of the depth-averaged model for Barnegat Bay. This is the primary objective of the extended field data collection program.

b. Verify the accuracy of groundwater input estimates in the spatial domain. Conduct dye or drifter tests to determine the dispersion/diffusion coefficients in the two- or three-dimensional mass transport model, for better verification of groundwater input estimates and establishment of relationship between dispersion coefficients and wind.

- General Methodology

a. To achieve the first objective of revealing the wind-induced and tidal effects, at least three mooring stations will be installed within the Bay with, at least, two current sensors at each mooring station. The setup will be in operation for at least a month to fully record the wind-induced and tidal currents. The wind data will also be obtained from weather stations from the same period of time to make a correlation between the wind and the wind-induced current.

b. To achieve the second objective of verifying spatially the accuracy of groundwater input estimates, dispersion/diffusion coefficients must be determined in the field. Dye or drifters will be released instantaneously and tracked along their routes. The dye will be released at the same locations as the mooring stations to more accurately separate the advection and the dispersion.

- Expected Results and Applications

a. Assessment of wind-induced and tidal effects to assure applicability of the recommended hydrodynamic model, and a better relationship between bottom shear stress and depth-averaged velocity.

b. Values of dispersion/diffusion coefficients for spatial verification of groundwater input estimates by others and establishment of relation between dispersion/diffusion coefficients and wind.

c. A package of field data for the next phase of calibration and verification of the recommended hydrodynamic and mass transport model. These additional local field data, along with the bay-wide data gathered during the first year of the project, will form the necessary data base.

10.1.2. Other field data needs

To develop a versatile overall water quality model (not just circulation model) to guide the management, the following field data needs are identified:.

a. Sediment Data

The suspended sediment concentration needs to be measured as it is not only a water quality parameter itself, but also it affects light availability to primary production and is a substance dispersant.

The bottom sediment movement needs to be monitored as it affects bed-water column nutrient exchange and material burial. It also affects habitats for benthic organisms.

b. Improved bathymetry

The current available bathymetry is quite outdated, accuracy of bathymetry will affect hydrodynamic modeling greatly.

c. Hydrographic data outside the Bay

Tidal exchange between the Bay and ocean is very much affected by the flow pattern outside the Bay.

d. Surface stream flow and quality

At this time, flow and water quality were monitored only in the Toms River. Due to interaction between surface streams and groundwater, the Toms River information might not be easily extrapolated to other streams, or even just to the portion of the Tom River below the gaging station in the city of Toms River.

e. Groundwater flow and quality

The largest portion of the infiltrated water discharges via surface streams; however, a unknown portion is directly discharging into the Bay. Monitoring wells may need to be setup along the western land margin of the Bay to measure the direct groundwater input. The accuracy of the groundwater model could also be improved near the Bay area by obtaining better geologic information.

## 10.2. Numerical Modeling

The next phase is to incorporate some numerical modeling. It is recommended that a diagnostic run of a two-dimensional depth-averaged model be conducted at first using the hydrographic data already obtained through the study reported herein. Ideally, it should be conducted concurrently with the second year additional hydrographic data collection.

After the first year hydrographic study reported herein, the second year additional hydrographic data collection and the diagnostic run of a two-dimensional model, an appropriate circulation model should be able to be identified and developed. There is a possibility that further field data will need to be collected if a three-dimensional model is to be developed.

The framework of a comprehensive water quality model should be established at this time because some hydrographic data and water data are already available. It is envisioned that the comprehensive water quality model will include sub-components for the bay itself, for watersheds, for aquifers, for surface streams with proper consideration of interaction with groundwater, coastal ocean, and even the nearby airshed. In this computer age, development of such a comprehensive model is not a difficult and costly task because there are existing models for all sub-components. What left to be done is to select appropriate models incorporating the knowledge of the features of Barnegat Bay and the availability of field data, and to link them together efficiently.

## 11.0 Summary and Conclusions

The three objectives of the project have been achieved. The summary and conclusions regarding these three objectives are:

a. Provide NJDEP with a set of field data for a preliminarily-recommended numerical circulation model.

This is the primary objective of the project. A set of field data have been collected. The instrument locations are shown in Fig. 7.1. Instruments were deployed during three time periods, December, 1994-January, 1995, May-June, 1995, and June-July, 1995.

Instruments were deployed at boundaries of the Bay to gather long-term data for driving a numerical circulation model. Tidal gages and portable S-4 metering systems [field data logger with probes to simultaneously measure the environmental variables of current velocity (in two directions), conductivity, and temperature] were installed at Barnegat Inlet (east open boundary), Surf City (southern open boundary), and Mantoloking (northern open boundary). There is an existing flow gage in the Toms River to provide information at the land-water boundary. Meteorological data are available at the air-water boundary.

The Marsh-McBirney current velocity meters and the ADCP were also used for measuring the current velocity profiles at those three open boundaries.

Instruments were deployed within the Bay to gather field data to calibrate and verify a numerical circulation model. There are two types of data which were collected within the Bay. One is the long term data, e.g., one month, at certain points, to provide information about temporal variation. Another type is short term data, e.g., one tidal cycle, at certain transects to provide information about spatial variation. There exist three tidal gage stations within the Bay. These tidal records are continuous and of long term. Three S-4 stations were setup within the Bay to gather continuous data of water surface elevation, current velocity, conductivity, and temperature for one month in winter, one in spring, and the last in summer. One station was placed outside Cedar Creek (south of the Toms River) to record information in the middle portion part of the Bay Another was set up near Loveladies to take advantage of the existing tidal gage and to record information within the southern part of the Bay. The last one was placed outside Silver Bay in the northern portion of the Bay.

Velocity profiles, salinity profiles, temperature profiles, and water surface elevations were measured at three interior transects (Cedar Creek, Loveladies, and Silver Bay) for a time period of one tidal cycle or less. The CTD (Conductivity-Temperature-Depth) metering system was used to record conductivity and temperature profiles. The Marsh-McBirney current velocity meters and ADCP were used for measuring the current velocity profiles.

These profiles at three transects, along with the long-term data gathered within the Bay and at the boundaries, for three time periods, form a set of data for driving, calibrating, and verifying a two-dimensional depth-averaged numerical circulation model.

b. Provide NJDEP with a preliminary assessment of circulation pattern and its impact on pollutant transport based on the collected field data.

Results of the preliminary assessment of circulation pattern are summarized follows:

Tidal flushing time: The average tidal flushing time was estimated to be approximately 58 days. The flushing time was calculated using the continuous salinity data at Barnegat Inlet obtained by this hydrographic study. The tidal exchange rate was calculated at first and then it was used to calculate the flushing time. On average, only thirty-seven percent of the flood tide volume passing through Barnegat Inlet is new ocean water which can mix with the Bay water and dilute pollutants. Sixty three percent is returning Bay water with similar water quality.

Horizontal distribution of salinity and temperature: There exists a horizontal salinity gradient in the Bay, highest near the Inlet, lowest at locations away from the inlet and adjacent to surface streams. Temperature is quite uniform in the horizontal plane in summer, while it varies spatially in winter.

Vertical distribution of salinity and temperature: Salinity is generally quite uniform in vertical direction, except at areas close to the Inlet during flood tide. Temperate is uniform in the vertical direction. These indicate Barnegat Bay, in general, is well-mixed in the vertical direction.

Flow pattern (circulation pattern): The flow is in general in the north-south orientation of the Bay. In the south and middle portions of the Bay, the north-south current is dominated by tidal influence; however, wind is inducing a two-layer (surface-bottom) current structure in the east-west orientation. Existence of the two-layer current structure accelerates pollutant mixing from west to east and discharging to the ocean. In the northern portion of the Bay, due to its far distance from the inlet and its shallowness, the wind is the dominant driving force. The wind is inducing the two-layer current structure in both an east-west orientation, and in a north-south orientation. Pollutants introduced into this portion of the Bay will be mixed faster than in the southern and middle portions of the Bay.

c. Provide NJDEP with a recommendation on the numerical circulation model.

Based on preliminary assessment of the circulation pattern, a two-dimensional depth-averaged circulation model is recommended for Barnegat Bay at this stage. However, due to existence of the two-layer current structure induced by wind, especially in the northern portion of the Bay, additional field data are needed to reduce uncertainties in model verification, especially those which would help to establish relations between the wind and the Manning's coefficient and the dispersion coefficients.

A layered (for example, two layers) version of the three-dimensional model should be also considered for Barnegat Bay because of the strong wind effect. A layered version of the three-dimensional model will solve for the two-layer current structure directly, thus disassociating the wind and calibration coefficients. However, additional data on the two-layer current structure, for example, using two current velocity sensors in the vertical direction for a long-term period of time at the boundary and within the Bay, must be collected to properly calibrate and verify a layered version of the three-dimensional model.

## 12.0 Implications for Management

In response to a growing concern about the impacts of development, the New Jersey Legislature passed an Act requiring a study of the nature and extent of development impacts upon the Bay. To assess the impacts, a water quality model will need to be established. The pollutant transport process in the Bay is critical to the water quality, and the transport is mostly determined by the circulation pattern.

This study provides the necessary hydrographic information to drive, calibrate, and verify the hydrodynamic (transport) component of a proposed water quality model. A two-dimensional depth-averaged model is preliminarily recommended at this stage. In addition, analysis of the gathered field data has provided a preliminarily knowledge of the Bay circulation pattern.

One significant finding thus far was (using field data and a zero-dimensional model) that average flushing time for pollutants in Barnegat Bay is on the order of 58 days.

Information for mean condition is valuable because it establishes a consideration of the overall bay condition, such as total watershed nutrient contribution versus total ocean nutrient contribution. Continuous salinity data collection at Barnegat Inlet reveals that, on average, only thirty seven percent of the ocean water entering on the flood tide is new ocean water. This number is very important in determining amount of nutrients which are contributed from the ocean.

If it is determined, for example, nutrients are mostly contributed from the ocean and atmosphere, management programs applied to watersheds, septic tanks, and local marinas will not be effective to improve water quality in the Bay. It is strongly recommended that hydrographic information gathered through this research project be applied to study the nutrient budget as soon as possible.

The obtained tidal exchange rate (thirty seven percent) is also very important in determining amount of direct ground water seepage into the Bay. The direct ground water seepage was calculated to be relatively small, which is in agreement with U.S.G.S.'s estimation based on output from a three-dimensional groundwater model. This implies that nutrient contribution from this source is also relatively small. Since U.S.G.S. has a long-term record of water quantity and quality for surface streams, and since direct groundwater seepage into the Bay is relatively small, we should be able to obtain a good estimate of nutrient contribution from freshwater sources, especially for the Toms River. Furthermore, it becomes possible to use gathered stream flow and quality information to evaluate effectiveness of source control programs applied to watersheds and septic tanks.

In addition, the obtained tidal exchange rate will help to define pollutant mixing zone outside the Barnegat Inlet. Location of the wastewater effluent outfalls relative to the mixing zone determines the portion of wastewater discharge which will return to the Bay.

Our recently gathered field data indicate that a depth-averaged two-dimensional model will provide sufficient spatial information for various management scenarios, e.g. impacts of management of individual small watersheds leading to the Bay. Our data reveals that the Bay is not fully mixed in the horizontal plane. Therefore, contributions from individual watersheds could be spatially restricted. We like to have a model which distinguishes between the northern portion and the southern portions of the Bay. Further, because land-based management will mostly affect the western portion of the Bay, we like to have a model which will also distinguish between the western and the eastern portions of the Bay. Thus, it is apparent a two-dimensional model is necessary from the management point of view.

Fortunately, our field data reveal a well-mixed condition in the vertical direction. From this point of view, a three-dimensional model is unnecessary. However, if wind induces a strong layered current structure in the vertical plane, which not only makes mixing faster in the vertical plane, but also in the horizontal plane, it may be necessary to use a three-dimensional model to solve for the current structure on the vertical plane to improve the quantification of the mixing in the horizontal plane. To quantify horizontal mixing properly is very important because it will improve knowledge of the impacts of managing an individual sub-watershed (e.g., Toms River) on the entire Bay.

Future field data collection should be directed, within the budget constraint, toward developing a depth-averaged two-dimensional model.

## 13.0 Bibliography


Ambrose, R. B., Wool, T. A., Martin, J. L., Connolly, J. P., and Schanz, R. W. (1991). WASP5, A Hydrodynamic and Water Quality Model -- Model Theory, User's Manual, and Programmer's Guide. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Athens, Georgia.

Amein, M. and Cialone, M. A. (1994). DYNLET 2.0, Manual. Consulting Analysis Group, Inc., Raleigh, NC.

Apicello, G., Schuepfer, R. O'Connor, J. Zaccagino, and L. Kloman (1993). "Water Quality Modeling of Combined Sewer Overflow Effects on Newtown Creek (NY)." Proceedings of 66th Annual Conference and Exposition, Water Environment Federation, Anaheim, CA, October 3-7.

Asheley, G. M. (1987). Tidal Prism Study, Barnegat Inlet, New Jersey, Final Report to U.S. Army Corps of Engineers, Philadelphia District, PA. Rutgers University, September.

Carpenter, J. H. (1963). Concentration Distribution for Material Discharged into Barnegat Bay. Pritchard-Carpenter, Consultants and The Johns Hopkins Univ., Unpub. Tech. Rept., 13 p.

Blumberg, A. F. and Mellor, G. L. (1987). "A Description of a Three-Dimensional Coastal Ocean Circulation Model." Three Dimensional Coastal Ocean Models, N. S. Heaps, ed., American Geophysical Union, Washington, D. C..

Butler, H. L. (1978). Numerical Simulation of Tidal Hydrodynamics: Great Egg Harbor and Corson Inlets, New Jersey, Technical Report H-78-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cerco, C. F. and Cole, T. (1993). "Three-Dimensional Eutrophication Model of Chesapeake Bay." Journal of Environmental Engineering, American Society of Civil Engineers, Vol. 119, No. 6.

Cerco, C. F., Bunch, B., Cialone, M. A., and Wang, H. (1994). Hydrodynamics and Eutrophication Model Study of Indian River and Rehoboth Bay, Delaware. Technical Report EL-94-5, U.S. Army Corps of Engineers, Waterways Experiment Station, May.

Cheng, R. T. and Smith, P. E. (1990). "A Survey of Three-Dimensional Numerical Models." Estuarine and Coastal Modeling, Proceedings of the Conference, American Society of Civil Engineers, New York, NY.

Cheng, R. T., Casulli, V., and Gartner, J. W. (1993). "Tidal, Residual, Intertidal Mudflat

(TRIM) Model and its Applications to San Francisco Bay, California Bay." Estuarine, Coastal, and Shelf Science, Vol. 36, pp. 235-280.

Chizmadia, P. A. Kennish, M. J., and Ohori, V. L. (1984). "Physical Description of Barnegat Bay, NJ." M. J. Kennish and R. A. Lutz, editors, Springer-Verlag, New York, NY.

Cialone, M. A. (1990). "Curvilinear Long Wave Hydrodynamic (CLHYD) Model for Tidal Circulation and Storm Surge Propagation." Estuarine and Coastal Modeling, Proceedings of Conference, M. L. Spaulding, ed., American Society of Civil Engineers, New York, NY.

Feigner, K. D. and Harris, H. S. (1970). Documentation Report --FWQA Dynamic Estuary Model. U.S. Department of the Interior, Federal Water Quality Administration.

Fischer, H. B., List, E. J., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). Mixing in Inland and Coastal Waters, Academic Press, Inc., San Diego, CA.

Harleman, D. R. F., Dailey, J. E., Thatcher. M. L., Najarian, T. O., Brocard, D. N. and Ferrara, R. A. (1977). User's Manual for the M.I.T. Transient Water Quality Network Model Including Nitrogen-Cycle Dynamics for Rivers and Estuaries. EPA-600/3-77-010, R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology.

Ippen, A. (1966). Coastal and Estuarine Hydrodynamics, Academic Press, Inc., New York, NY.

Johnson, B., Kim, K., Heath, R., Hsieh, B., and Butler, L. (1993). "Validation of a three-dimensional hydrodynamic model of Chesapeake Bay." Journal of Hydraulic Engineering, American Society of Civil Engineers, Vol. 199, No.1, pp. 2-20.

Kennish, M. J. And Lutz, R. A. (1984). Ecology of Barnegat Bay, New Jersey. Springer-Verlag, New York, NY.

King, I. P. (1985). "Strategies for finite element modeling of three-dimensional hydrodynamic systems." Adv. Water Resour., Vol., 8, pp. 69-76.

Martin, M. (1989). "Ground-water flow in the New Jersey coastal plain." U.S. Geological Survey Open File Report 87-528, West Trenton, NJ.

Masch, F. D., Brandes, R. J., and Reagan, J. D. (1977). Numerical Simulation of Hydrodynamics. U.S. Army Corps Eng., Coastal Eng. Res. Cent. and U.S. Army Eng. Waterways Exp. Stn., Tech Rep. GITI-6, Vol., Appen. 2, 123 pp.

Moser, F.C., S.P. Seitzinger, R.G. Lathrop, and R.J. Murnane, (1995). " Understanding productivity and nutrient loading in a shallow, back-bay estuary: Barnegat Bay." Estuaries, in prep.

Najarian, T. O. and Harleman, R. F. (1989). "Role of Models in Estuarine Flow and Water Quality Analysis." Estuarine Circulation, Neilson, B. J., Brubake, J., and Kuo, A., eds., The Humana Press Inc.

Najjar, K. F. (1989). Mathematical Modeling of Stormwater Pollution in a Tidal Embayment. Ph.D. Dissertation, Rutgers University, New Brunswick, New Jersey.

New Jersey Department of Environmental Protection and Energy (1993). A Watershed Management Plan for Barnegat Bay, Trenton, NJ, June.

New York City Department of Environmental Protection (1993). "Catalog of Hydrodynamic and Water Quality Models of New York Harbor Vicinity." New York, NY.

Nicholson, R. (1995). Personal Communications. U.S.G.S., West Trenton, NJ.

Psuty, N., Guo, Q., and Suk, N. (1993). Sediments and Sedimentation in Great Egg Harbor Bay, New Jersey, Final Report, Rutgers University, New Jersey, December.

Riley, M. J. And Stefan, H. (1987). "Dynamic Lake Water Quality Simulation Model - MINLAKE." Project Report No. 263, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, August.

Rogers, Golden and Halpern, Inc. (1990). Profile of the Barnegat Bay, Prepared for the Barnegat Bay Study Group, in association with Expert Information Systems, Inc., March.

Scheffner, N. W., Vemulakonka, S. R., Mark, D. J., Butler, H. L., and Kim, K. W. (1994). New York Bight Study, Report 1: Hydrodynamic Modeling. Technical Report CERC-94-4, U.S. Army Corps of Engineers, Waterways Experiment Station, August.

Schuepfer, F. E. (1988). "Hydrodynamic Model of Great Sound, New Jersey." Marine Geology, Vol. 82, pp.1-5.

Seaburgh, W. (1995). Personal Communications, U.S. Army Corps of Engineers, Waterways Experiment Station, Visckburg, Mississippi.

Seaburgh, W., Cialone, M. A., and McCormick, J. W. (1995). "Hydraulics of Barnegat Inlet, NJ." To be published in the Journal of Coastal Research.

Sheng, Y. P. (1986). "A Three-Dimensional Mathematical Models for Coastal, Estuarine, and Lake Currents Using Boundary Fitted Grid," A.R.A.P. Report No. 585, Aeronautical Research Associates of Princeton, Inc., Princeton, NJ.

Signell, R. P., Jenter, H. L., and Blumberg, A. F. (1993). "Modeling the Seasonal Circulation in Massachusetts Bay." Estuarine and Coastal Modeling III, Proceedings of the 3rd International Conference, American Society of Civil Engineers, New York, NY.

Thomas, W. A., and McAnally, W. H., Jr., 1985. "User's Manual for the Generalized Computer Program System; Open-Channel Flow and Sedimentation, TABS-2, Main Text and Appendices A through O," Instruction Report HL-85-1, U.S. Army Corps Engineer Waterways Experiment Station, Vicksburg, MS.

Watt, M. K., Johnson, M. L., and Lacombe, P. J. (1994). "Hydrology of the Unconfined Aquifer System, Toms River, Metedconk River, and Kettle Creek Basins, New Jersey, 1987-90." U.S. Geological Survey, Water Resources Investigation Report 93-4110, West Trenton, New Jersey.

## 14.0 Listing of All Participants and Activities on Project

This project necessitated the active participation of many people in the various phases of data gathering, data reduction, field work, data analyses and report preparation. Many of the individuals participated in several aspects of the projects. Some were active only in the most arduous tasks. The general team consisted of Dr. Norbert P. Psuty and Dr. Scott Glenn of the Institute of Marine and Coastal Sciences, and Dr. George Guo, George P. Lordi, and Mathew R. Mund of the Civil and Environmental Engineering Department. All of the above were active in the field phase of data gathering. They were ably assisted by Nam Soo Suk, Roger Hoden, Damian O'Grady, Walt D. Svekla Jr., Stefanie DeFiglia, Michael Craghan, Kevin Kajetzke, Ron Lockwood, Hung-I Chan, Chip Haldeman. Hai Pan assisted in conducting the time-series analysis of S-4 current data. Don Launer, Bill Towhey, Jim Mason, Gary Pearle, Peter Smith, and Joseph Williams of the Barnegat Bay Watch Program volunteered their boats for data collection. Surf City Marina and Surf City Yacht Club provided a location for the SIGMA Model Bubbler Transducer for level measurement. Liz Creed provided assistance with the operation and maintenance of the S-4 Current Meter. Jim Nichols of the New Jersey Marine Sciences Consortium and Tim Deering of the University of Delaware provided information concerning the S-4 Current Meter. Michael Kennish and Jay Vouglitois assisted in obtaining background information of Barnegat Bay.

The U.S. Army Corps of Engineers (Keith Watson, Jeff Gerbert, Joe Scolari of Philadelphia District, Bill Seaburgh, and Mike Tubman of WES) provided their assistance, boat, and ADCP to gather data. U.S. Geological Survey (Tony Navoy, Ward Hickman, Bob Nicholson, and Woody Centinaro of West Trenton Office) provided tidal elevation, surface streamflow, and groundwater information. The U.S. Coast Guard (Fifth Coast Guard District) allowed permission to use Barnegat Bay aids-to-navigation as locators for the placement of long term instruments. Dr. Mary Cialone of WES, Dr. Philip Liu of NJDEP, Dr. Allen Blumberg of HydroQual, Dr. Tavit Najarian, Hugh Tipping of NYCDEP, Dave Paterson of DRBC, Barbara Donnel of WES, Walter Ewald of LMS, John McCormick of USCOE provided information on numerical models.

A workshop on Hydrographic Study of Barnegat Bay was conducted at Rutgers University on July 27, 1995. Participants provided valuable technical inputs during and after the workshop. They are, besides project team members, Dr. David Tolmazin of USEPA, Drs. Mary Gastrich and Philip Liu of NJDEP, Dr. Andreas Munchow and Fredrika Moser of Rutgers University, Bob Nicholson, Ward Hickman and Katherine Kariouke of U.S.G.S., and John McCormick of USCOE.

The project was managed by Dr. Mary Gastrich of New Jersey Department of Environmental Protection, Division of Science and Research.